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Vibration Analysis of Modern Fire Apparatus

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Vibration Analysis of Modern Fire Apparatus

A Major Qualifying Project Report

Submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

Submitted by:

Zachary Stephen Haase

Date: May 27, 2012

Approved:

Prof. M. S. Fofana

Abstract

In 2005, the National Fire Protection Association was made aware that mission critical firefighting electronics were being damaged irreparably while in service on large, diesel-powered fire apparatus. It was subsequently identified that the products of two anonymous and independent manufacturers were being destroyed due to vibration exposure while on pumper type apparatus. Due to the complete absence of vibration data, the response of the NPFA was to design a test that replicated the results, but not the means.

A purpose-built, novel sensor was developed to facilitate vibration recording of modern fire apparatus. A front-end recording virtual instrument was developed using the National Instruments LabView suite. A second virtual instrument was designed to normalize the data to standard gravity and to characterize its spectral content. Preliminary baseline tests showed that the low-cost sensor provided adequate signal to noise ratios. Vibration characterization of pumper apparatus revealed pump induced vibrations were in excess of 0.26 g. Documentation and instructions on the operation of the sensor are contained herein for usage in subsequent vibration recording of fire apparatus.

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Glossary of Terms

DOT	Department of Transportation
Engine	Typical designation for pumper or initial attack appartus
FAMA	Fire Apparatus Manufacturers' Association
FFT	Fast Fourier Transform
FHWA	Federal Highway Administration
gpm	Gallons Per Minute
GVW	Gross Vehicle Weight
Ladder	Typical designation when used to describe aerial or quint apparatus
LDH	Large Diameter Hose
MEMS	Micro Electro-Mechanical System
Monitor	A high throughput water nozzle or "cannon"
MQP	Major Qualifying Project
NFPA	National Fire Protection Agency
PTO	Power Take-Off
Quint	A type of fire apparatus that is a combination of pumper and aerial apparatus
RSE	Referenced Single Ended mode (operation mode of LabView A/D converters)
SCBA	Self-Contained Breathing Apparatus
SFD	Sterling Fire Department
SNR	Signal-to-Noise Ratio
Tower	A basket or bucket at the end of an aerial or quint apparatus
Tower Ladder	Aerial or quint apparatus employing a tower

Truck	Typical designation for aerial or quint apparatus
VI	LabView Virtual Instruments

Acknowledgements

Heartfelt thanks must first be extended to Professor Mustapha Fofana for his support and constant encouragement of this project. Thanks to Professor Paul Cotnoir who provided the inspiration for this work.

Thanks to Chief David Hurlbut and Lt. Kevin Grebinar of the Sterling Fire Department for graciously allowing vibration recordings to be made during department training exercises.

Thanks to Lt. Andrew White and Chief John Sullivan of the Worcester Fire Department as well as firefighters Angie and Chris of the Franklin Street Station for providing insight into some of the vibration damages observed in the city's fire apparatus.

Thanks, also, to the Electronic Safety Equipment technical committee of the National Fire Protection Association under the guidance of Chief Bruce Varner for its ongoing efforts to develop standards to improve firefighter safety.

CHAPTER 1: Fire Apparatus and Vibrations

1.1 Motivation and Significance

In 2005, the National Fire Protection Agency (NFPA) was made aware that mission critical firefighting electronics were being damaged irreparably while in service on large, diesel-powered vehicles. It was subsequently identified that the products of two anonymous and independent manufacturers were being destroyed due to vibration exposure while on an operating pumper. Due to the complete absence of vibration data, the response of the NPFA was to design a test that replicated the results, but not the means. With the possibility of future NFPA specifications requiring vibration testing, baseline data that more accurately replicates the actual environment would be desired.

1.2 Objectives

The first objective of this Major Qualifying Project (MQP) was a literature review of the types and specifications of fire apparatus. The second objective was development of a sensor and data acquisition system capable of measuring vibrations of representative fire apparatus. The final objective was to use the sensor and data acquisition system to measure and analyze actual vibration, identifying maximum acceleration levels and frequency content.

1.3 Order of Report

Chapter 2 provides a background literature review and profiles the types of fire apparatus that are used throughout the United States. Additional discussion is provided identifying fire apparatus manufacturers. The chapter is concluded with a discussion on the impact of vibration on both equipment and personnel. Chapter 3 describes the experimental planning and the design of the data acquisition system, including calibration and system validation. The remaining sections of the chapter provide results and analysis of measurements of pumper apparatus conducted with the Sterling Fire Department. Chapter 4 provides concluding remarks and recommendations for future research efforts. Additional appendices are provided for reference.

CHAPTER 2: Background

2.1 Introduction

In 2005, the National Fire Protection Agency was made aware that mission critical firefighting electronics were being damaged irreparably while in service on large, diesel-powered vehicles. It was subsequently identified that the products of two anonymous and independent manufacturers were being destroyed due to vibration exposure while on an operating pumper. Due to the complete absence of vibration data, the response of the NPFA was to design a test that replicated the results, but not the means.

This chapter is intended to provide background information on the types of fire apparatus. Classification as well as regulatory dimensions and weights are provided. A comprehensive list of manufacturers and manufacturers' suppliers is presented. Tasks and functions of modern day fire apparatus are defined. NFPA function-based standards are detailed. Finally a brief discussion of vibration is provided.

2.2 Classification of Fire Apparatus

A typical fire department operates a wide variety of vehicle apparatus in order to fulfill its role of fire prevention and mitigation. Many factors influence a fire department's choice of apparatus, including but not limited to:

1. Coverage area
    a. Geographic distribution of stations
    b. Desired/applicable response time
    c. Availability of hydrants
        i. Quality: how many hydrants are necessary to suppress a given fire?
        ii. Drafting: is it necessary for a tanker to shuttle water?
    d. Road limitations
        i. Maximum allowable vehicular weights (e.g. bridges, road makeup)
        ii. Vehicle height limitations (e.g. low clearance issues such as low bridges)
        iii. Maneuverability and minimum turning radii (refer to Figure 1)
2. Coverage area structural makeup
    a. Percentage makeup of residential, commercial, and industrial
    b. Height of representative/typical structures
    c. Square footage of representative/typical structures
3. Personnel
    a. Number of firefighters
    b. Type of staffing such as volunteer, call, or career

    c. Availability and response time of call and volunteer personnel

4. Type of fire

    a. Classic “structural” (i.e. typical wood-based residential construction)

    b. Industrial (may require foam applications)

        i. Specialized chemical considerations (e.g. magnesium factory)

        ii. Overly energetic materials (e.g. oil refinery)

    c. Airports (require rapid and sometimes off-road response)

Figure 1 Maneuverability considerations for a pumper, Lombard Street, San Francisco, CA[1]

Careful selection of the appropriate type of fire apparatus must be made by the fire department. In the United States, the selection and definition of the apparatus type is made using the industry accepted standard NFPA 1901, *Standard for Automotive Fire Apparatus*. The current publication of this document is the 2009 edition. The 204 page document specifically identifies the key requirements for seven classifications of fire apparatus. Specifics of the various classifications can be found in this report on the following pages:

- Pumper Fire Apparatus (page 26)
- Initial Attack Fire Apparatus (page 32)
- Mobile Water Supply Fire Apparatus (page 37)
- Aerial Fire Apparatus (page 41)
- Quint Fire Apparatus (page 48)
- Special Service Fire Apparatus (page 54)
- Mobile Foam Fire Apparatus (page 58)

2.3 Size, Weight, and Capacity

Fire apparatus are available in a wide range of sizes. Generally speaking, the size of the apparatus is related to the function the vehicle performs. Considering that a fire apparatus is designed for rapid response, virtually all apparatus built today are designed for operation as an unrestricted vehicle. That is, they are designed with maximum “normal” heights, lengths and weights.

Interestingly, the sizes of vehicles in the United States are regulated by both state and federal Department of Transportation (DOT) regulations. The Federal Highway Administration (FHWA) establishes rules for commercial motor vehicles as follows:

Table 1 DOT FHWA vehicle dimension standards[2]

	Single Unit	Semitrailer
Width	2.6 m (102.36 in.)	2.6 m (102.36 in.)
Height	No federal limit Most states: 13.5 – 14.0 ft.	No federal limit Most states: 13.5 – 14.0 ft.
Length	N/A	48 ft. trailer min

Table 2 DOT FHWA vehicle weight standards[3]

Single Axle	20,000 pounds
Tandem Axle	30,000 pounds
Gross Vehicle Weight	80,000 pounds

In 1975, Congress enacted the *Bridge Formula* which established the relationship between vehicle length and axle loads. In essence, this is a means of calculating the "pressure" a vehicle exerts on a bridge. An example diagram relating to the formula can be found in Figure 2. The formula is as follows: [4]

$$W = 500 \left[\frac{LN}{N-1} + 12N + 36 \right]$$

where,

- W = the overall gross weight on any group of two or more consecutive axles to the nearest 500 pounds.
- L = the distance in feet between the outer axles of any group of two or more consecutive axles.
- N = the number of axles in the group under consideration.

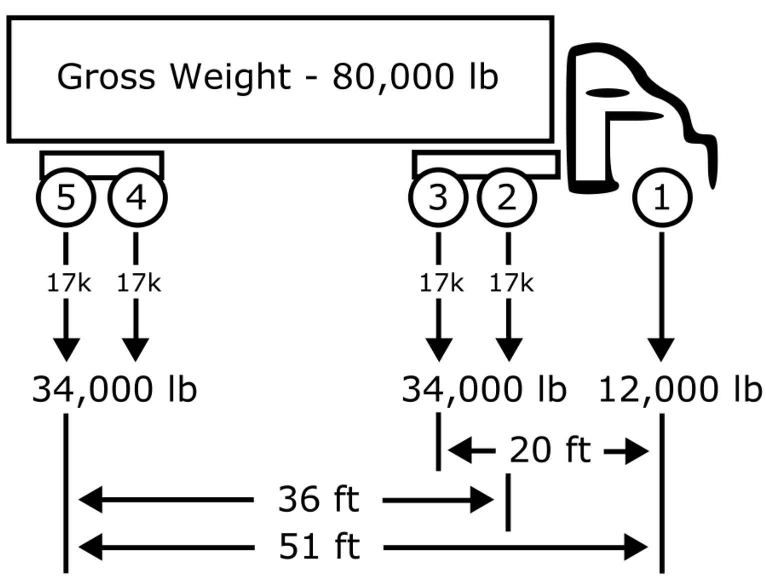


Figure 2 Example of bridge formula consideration using FHWA axle maximums[5]

Most state DOT standards are similar, but there is variation. Documenting the specifics of all fifty states is unnecessary for the purposes of this report. In order to show the dimensions and weights in general, two states were chosen at random from the DOT FHWA website. Colorado and California DOT standards are as follows:

Table 3 Example state DOT vehicle dimension standards[6,7]

	Colorado Single Unit	Colorado Semitrailer	California Single Unit	California Semitrailer
Width	102 in.	102 in.	8.5 ft.	8.5 ft.
Height	13.0 ft.	13.0 ft.	14.0 ft.	14.0 ft.
Length	45 ft. max	57 ft. 4 in. trailer max	40 ft. max	65 ft. max overall length

Table 4 DOT axle weight limitations for Colorado and California[8,9]

	Colorado [pounds]	California [pounds]
Single Axle	20,000	20,000
Tandem Axle	30,000	30,000
Single Unit (2 Axle)	36,000	40,000
Single Unit (3+ Axle)	54,000	54,000
Semitrailer GVW	80,000	80,000

Capacities of fire apparatus again depends upon the configuration of the vehicle. Thorough discussion of capacities may be found in 2.7 Standards and Development on page 25.

2.4 Manufacturers and Builders

The Fire Apparatus Manufacturers' Association (FAMA) is a non-profit trade association that is focused on protecting and advancing the fire and emergency services industry. While FAMA does not create any standards directly, its members support the research and development of "performance-based minimum standards related to the manufacture of fire apparatus and equipment." Comprised of members representing the manufacturers position within the nine NFPA interest categories, many FAMA members contribute to the development of NFPA 1901, with one representing FAMA's interests directly.[10]

The following is a comprehensive list of the members of the FAMA. As all of these companies either manufacture fire apparatus or furnish equipment for use therein, all members will be included here for exactness.[11]

- 4-Guys Inc. 230 Industrial Park Rd., Meyersdale PA 15552
- A & A Manufacturing Co., Inc. 2300 S. Calhoun Road, New Berlin WI 53151
- Action Coupling & Equip., Inc. 8248 County Road 245, Holmesville OH 44633
- Akron Brass Co. PO Box 86, Wooster OH 44691
- Alexis Fire Equipment Co. 109 East Broadway, Alexis IL 61412
- Allison Transmission, Incorporated 4700 West 10th Street, Indianapolis IN 46222
- Aluminum Ladder Company W Darlington St., Florence SC 29502
- AMDOR, Inc. P.O. Box 810, Lewiston NY 14092
- American LaFrance LLC 1090 Newton Way, Summerville SC 29483
- Amity Fire and Safety, Inc. 3750 Chestnut Street, Alburtis PA 18011

- Apparatus Equipment & Service, Inc. 969 West 2100 South, Salt Lake City UT 84119
- Arnprior Fire Trucks Corp. 10 Didak Drive, Arnprior ON k7s 0c3
- Bauer Compressors. Inc. 1328 AZALEA GARDEN ROAD, Norfolk VA 23502
- Boise Mobile Equipment, Inc. 900 Boeing St., Boise ID 83705-3959
- Bostrom (H.O.) Company, Inc. 818 Progress Avenue, Waukesha WI 53186
- Brand FX Body Company 4995 Keller Haslet Road, Keller TX 76244
- Bulldog Fire Apparatus, Inc. 17 Winter Street, Woodville MA 01784-0058
- C.E. Niehoff & Company 2021 Lee St, Evanston IL 60202
- C.E.T. Fire Pumps Mfg. Ltd. 75 Hector Street, Pierreville QC J0G 1J0
- Carl Thibault Fire Trucks, Inc. 38, Thibault Street, Pierreville QC J0G 1J0
- Cast Products Inc. P.O. Box 1202, Athens AL 35611
- Class 1, Inc. 607 NW 27th Ave, Ocala FL 34475
- Classic Fire LLC 4534 W. Highway 40, PO Box 4529, Ocala FL 34475-3476
- Code 3 Inc. 10986 No. Warson Rd., St. Louis MO 63114-2029
- Command Light 1303 E. 11th St., POB 87, Loveland CO 80537
- Crimson Fire 1828 Freedom Road, Lancaster PA 17601
- Crimson Fire Aerials 1828 Freedom Road, Lancaster PA 17601
- Cummins Inc. 500 Jackson Street, Columbus IN 47201
- Cummins Onan 1400 73rd Avenue, N.E., Minneapolis MN 55432
- Custom Fab & Body LLC 158 US Hwy 45, Marion WI 54950-0125
- Custom Fire Apparatus Inc. 509 68th Avenue, Osceola WI 54020
- Danko Emergency Equipment 302 E 4th St, PO Box 218, Snyder NE 68664-0218

- Deep South Fire Trucks, Inc. 2342 Hwy. 49N, Seminary MS 39479
- Dependable Emergency Vehicles 275 Clarence Street, Brampton ON L6W 3R3
- Detroit Diesel Corporation 13400 Outer Drive West, Detroit MI 48239-4001
- Duo-Safety Ladder Corp. 513 West 9th Avenue, Oshkosh WI 54902
- E-ONE 1601 S.W. 37th Ave., Ocala FL 34474
- E.J. Metals 1201 Maple Creek Lane, New London WI 54961
- E.S. Safety Systems Inc. 960 Myrtle Rd. W., Ashburn ON L0B 1A0
- Eagle Compressors, Inc. 3003 Thurston Avenue, Greensboro NC 27406
- Elkhart Brass Mfg. Co., Inc. 1302 West Beardsley, Elkhart IN 46515
- Federal Signal Corporation 2645 Federal Signal Drive, University Park IL 60466-3195
- Ferrara Fire Apparatus, Inc. 27855 James Chapel, Holden LA 70744
- Fire Equipment Serv, div G&G PO Box 2542, Sumter SC 29151
- Fire Research Corporation 26 Southern Blvd, Nesconset NY 11767
- Firematic Mfg. Inc. 10 Ramsay Road, Shirley NY 11967
- FoamPro - Pentair Water 375 Fifth Ave NW, New Brighton MN 55112
- Fort Garry Fire Trucks 2521 Inkster Blvd, RR #2, Winnipeg MB R3C 2E6
- Fouts Bros. Fire Equipment 2158 Atlanta Road, Smyrna GA 30080
- Freightliner Trucks 2477 Deerfield Drive, Fort Mill SC 29715
- Gordon Aluminum Industries Inc 1000 Mason Street, Schofield WI 54476
- H & W Emergency Vehicles 3150 SW 234th, Suite #100, Hillsboro OR 97123
- Hale Products Inc. 700 Spring Mill Ave, Conshohocken PA 19428
- Hannay Reels, Inc. 553 St Rt 143, Westerlo NY 12193-0076

- Hansen International, Inc 130 Zenker Road, Lexington SC 29072
- Harrison Hydra-Gen, Inc. 14233 West Rd, Houston TX 77041
- Havis, Inc. (Main Office) 75 Jacksonville Road, Warminster PA 18974
- Heloc Fire Truck Ltee 1080,CHEMIN DESPRAIRIES, JOLIETTE QC J6E0L4
- Hendrickson USA, LLC 500 Park Boulevard, Itasca IL 60143-1285
- HMA LLC 7182 Hwy 14 / Suite 201, Middleton WI 53562
- HME, Inc. 1950 Byron Center Avenue, Wyoming MI 49519
- Horton Emergency Vehicles 3800 McDowell Road, Grove City OH 43123-
- Hydromotion Inc. 85 East Bridge Street, Spring City PA 19475
- ICL Perfornance Products LP 428 Buttonwood Road, Landenberg PA 19350
- IMMI 18881 US 31 North, Westfield IN 46074-0408
- Industries LaFleur, Inc. 2359 BOUL FISET, SOREL-TRACY QC J3P 5K2
- Intec Video Systems, Inc. 23301 Vista Grande, Laguna Hills CA 92653
- Kimtek Corporation 2163 VT RT 5A, Orleans VT 05860
- KME Fire Apparatus 1 Industrial Complex, Nesquehoning PA 18240
- Kochek Company Inc. 75 Highland Drive, Putnam CT 06260
- Kussmaul Electronics 170 Cherry Ave., West Sayville NY 11796
- Levasseur Fire Equipments 38 STE-ANNE STREET, St-Francois Du Lac GA J0G1M0
- Maintainer Custom Bodies, Inc. 909 So. East St., Rock Rapids IA 51246
- Marion Body Works, Inc. 211 W. Ramsdell St., Marion WI 54950-0500
- Maxi-Metal Inc 9345, 25th avenue, St-Georges QC G6A 1L1
- MaxxForce Engines 10400 W. North Ave., Melrose Park IL 60160

- Meritor, Inc. 14703 Forest Oaks Drive, Louisville KY 40245
- Metalfab Ltd. 847 Central Street, Centreville NB E7K 2E8
- Navistar 2701 Navistar Drive, Lisle IL 60532
- NEWMAR 2911 W. Garry Ave, Santa Ana CA 92704
- Oshkosh Corp. 3100 N McCarthy Road, Appleton WI 54913
- Performance Advantage Co. P.O. Box 306, Lancaster NY 14086
- Phenix Enterprises, Inc. 1785 Mount Vernon Avenue, Pomona CA 91768
- Pierce Manufacturing Inc. P.O. Box 2017, Appleton WI 54912-2017
- Plastisol Composites North America 101 Gerald L. Moses Drive, Groton NY 13073
- PPG Industries 1267 129th Ave., Coon Rapids MN 55448
- Pro Poly of America Inc. 230 NE 25th Avenue, Suite 300, Ocala FL 34470-7075
- PyroLance 20269 Smoky HIll Road, Ste. B-154, Centennial CO 80015
- RealWheels Cover Co. 3940 Tannahill Dr., Gurnee IL 60031
- Rescue 1 2201 Atlantic Avenue, Manasquan NJ 08736
- RocketFire 404 N Rte 115, PO Box 98, Roberts IL 60962-0098
- ROM Corporation 6800 East 163rd St., Belton MO 64012
- Rosenbauer America, LLC 100 Third Street, Lyons SD 57041-0057
- Seagrave Fire Apparatus LLC 105 East 12th St., Clintonville WI 54929-1590
- Seats, Inc. P.O. Box 60, Reedsburg WI 53959-0060
- Semo Tank 456 Semo Lane, Perryville MO 63775
- Signature 4 Fire Shopp 149 Harvest Drive, Coldwater OH 45828
- Smart Power Systems 5000 N. US 131, Reed City MI 49677

- Smeal Fire Apparatus Co. P.O. Box 8, Snyder NE 68664-0008
- Southern Fire Service & Sales, Inc. 229 Confederate Ave., Jasper GA 30143
- Spartan Chassis 1000 Reynolds Road, Charlotte MI 48813
- Spartan Motors, Inc. 1000 Reynolds Rd, Charlotte MI 48813
- Spencer Manufacturing Inc. 165 Veterans Blvd., South Haven MI 49090
- Stability Dynamics, div. Team Eagle Ltd. 10 Trent Drive, Campbellford AL K0L 1L0
- Stainless Flow Technologies 1020 Beier Road, Ripon WI 54971
- Sutphen Corporation PO Box 158, Amlin OH 43002
- SVI Trucks 1511 E. 11th St., Loveland CO 80537
- Task Force Tips, Inc. 3701 Innovation Way, Valparaiso IN 46383-9327
- Telma Retarder Inc. 870 Lively Boulevard, Wood Dale IL 60191
- Tempest Fireco Towers, LLC 4708 N. Blythe, Fresno CA 93722
- Thuemling Instrument Group, Inc. 1225 Pearl Street, PO Box 1625, Waukesha WI 53184-16215
- Toyne Fire Apparatus 104 Granite Avenue, Breda IA 51438
- Transportation Safety Technologies 2400 Roosevelt Ave., Indianapolis IN 46218
- Trident Emergency Products, LLC 2940 Turnpike Drive, Unit #9, Hatboro PA 19040
- Truck Cab Manufacturers Inc 2420 Anderson Ferry, Cincinnati OH 45238
- U.S. Coupling & Accessories, Inc. 2926 Columbia Hwy, Dothan AL 36303
- U.S. Tanker - Fire Apparatus 1827 Hobbs Drive, Delavan WI 53115
- United Plastic Fabricating Inc 165 Flagship Drive, North Andover MA 01845
- VisionMark, Inc. 2309 Industrial Dr., Sidney OH 45365-4219

- VT Hackney 911 West 5th St., POB 880, Washington NC 27889
- W.S.Darley & Company 325 Spring Lake Drive, Itasca IL 60143-2072
- Warn Industries 12900 S.E. Capps Rd, Clackamas OR 97015
- Waterous Company 125 Hardman Ave. So., So St. Paul MN 55075-1191
- Whelen Engineering Co.Inc. Rte 145, Winthrop Rd., Chester CT 06412-0684
- Wildfire 16311 NE Cameron Blvd, Portland OR 97230
- Will-Burt Co. 169 S.Main, Orrville OH 44667-0900
- Williams Fire & Hazard Control P.O. Box 1359, Mauriceville TX 77626
- Ziamatic Corp. 10 W Collelge Avenue, Yardley PA 19067

2.5 Design and Dimensions of Selected Fire Apparatus

Two pumper apparatus were chosen for the vibration test. The Sterling Fire Department graciously provided testing time on Engine 2 and Engine 4. The specifics of the vehicles are listed below in Table 5.

Table 5 Selected fire apparatus specifics

	Engine 2	Engine 4
Manufacturer	Pierce	Seagrave
Model	Saber	Marauder
Year	1997	2010
Length	31 ft, 5 in	31 ft, 8 in
Width	8 ft, 2 in	8 ft, 2 in
Height	10 ft	9 ft, 10 in
Gross vehicle weight	43,000 lbs	54,016 lbs
Tank size	1,000 gal	1,500 gal
Pump capacity	1,500 gpm	2,000 gpm
No. Seats	4	6

Manufacturer's literature may be found in Appendix E: Pierce Manufacturing Pumpers Brochure and Appendix F: Seagrave Fire Apparatus Pumper-Tanker Brochure.

2.6 Tasks and Functions of Fire Apparatus

The tasks and functions of fire apparatus are varied. Specifically, the role of a particular vehicle depends on the function that it is intended to provide. NFPA 1901 *Standard for Automotive Fire Apparatus* is the de facto standard for fire apparatus in the United States. This standard is defined in detail in Section 2.7 Standards and Development starting on page 25. In an overview sense, the chief functions of apparatus can be visualized using Table 6. These generic functions of fire apparatus are outlined here.

Table 6 Function matrix of common fire apparatus

	Pumper	Tanker	Aerial	Quint	Special
Aerial device			X	X	
Fire pump	X			X	
Tank	X	X		X	
Hose	X	X		X	
Ground ladders	X		X	X	
Minimum equipment	X	X	X	X	X
Personnel transport	X	X	X	X	X

2.6.1 Aerial Device

An aerial device is any powered telescoping or articulating arm which is designed to elevate and position firefighters. Additionally, these arms may be equipped with pre-piped waterways allowing firefighters to deliver large quantities of water via nozzles mounted at the end.

2.6.2 Pumping

Arguably, one of the most important aspects of any fire apparatus is the ability to pump water to suppress a fire. Historically, the first role performed by a specialized fire apparatus was that of pumping. Equipped with a manually operated water pump, these first apparatus were simultaneously being developed and produced in Saugus, MA, and England in the late 1670’s.

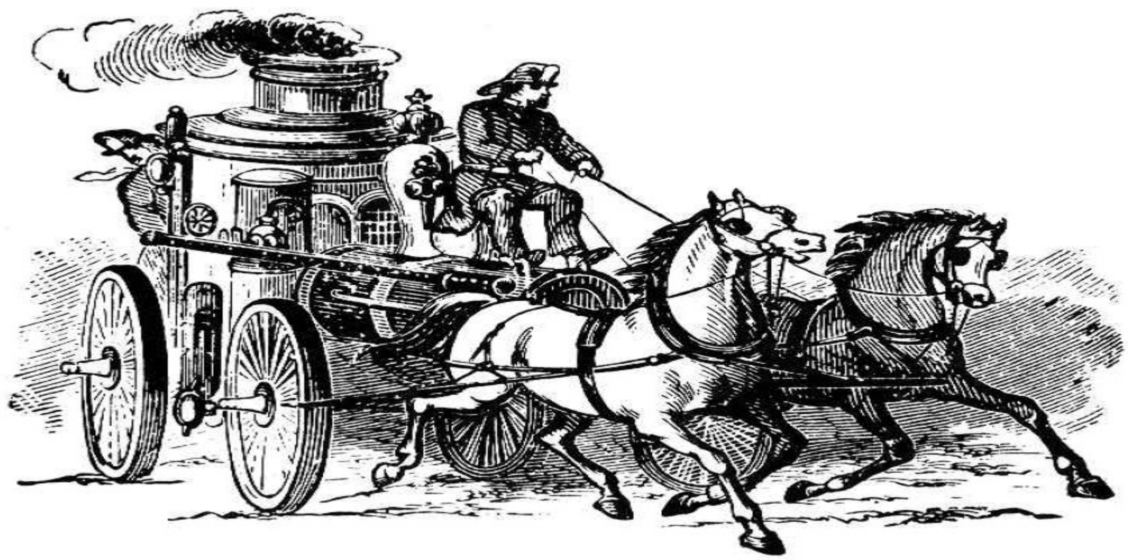


Figure 3 Example of early mechanized fire apparatus steam pumpers[12]

The first true fire “engine” was developed in London in 1829. This mechanized steam pumper (refer to Figure 3) reduced man-power requirements and greatly improved both pressure and volumetric flow.[13] These pumps, however, required large quantities of fuel to operate. In one case two steam pumps operating at a 1912 Richmond, VA, fire consumed over 25 tons of coal over a thirteen hour operating period.[14]

The first “modern” internal combustion pumpers appeared in the early 1900’s. The Knox Automobile Company in Springfield, MA, was one of the first manufacturers.[15] Many of these power-take-off equipped pumps operated reciprocating water pumps (refer to Figure 4).

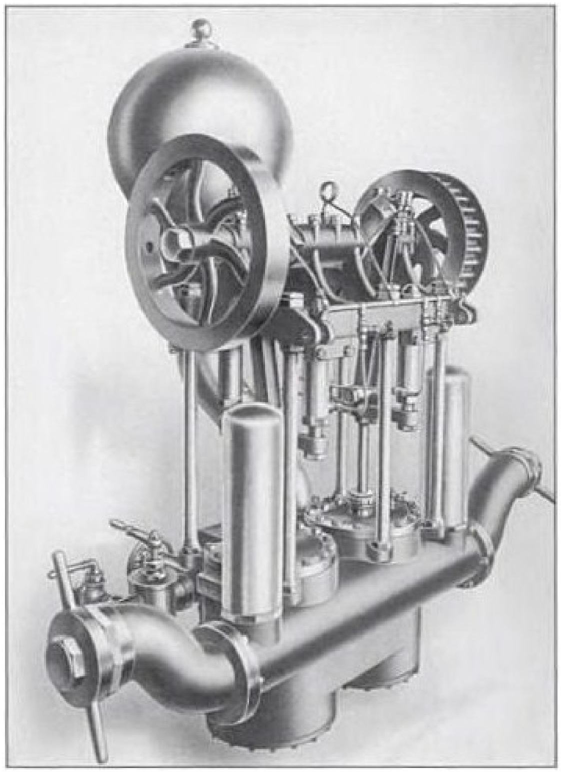


Figure 4 Example of a PTO pump from a 1900's Knox fire apparatus[16]

Modern day pumping operations are made possible by the ubiquitous centrifugal pump, an example picture of which is shown in Figure 5. Virtually every pumper in operation today uses this simple style of pump. The pump is usually operated using a power take-off (PTO) from the engine. When pumping operation is desired, the driver simply parks the pumper and proceeds to the pump panel which is usually located on the driver's-side of the apparatus (refer to Figure 6) or may be found spanning the chassis from side to side (refer to Figure 7). Once the vehicle is properly chocked to prevent movement, the driver will engage the PTO and commence pumping operations.

Waterous, a major pump manufacturer in the US has observed that the engines on most fire apparatus operating the USA today are typically governed between 1,800 and 2,100 rpm. The typical operating speeds of these same engines generally lie between 1,500 and 1,700 rpm. Since most water pumps average around 3,500 rpm to attain the volume and pressure levels required of NFPA 1901, these PTO systems typically employ a transmission with ratios in the region of 2.25 to 1.[17]

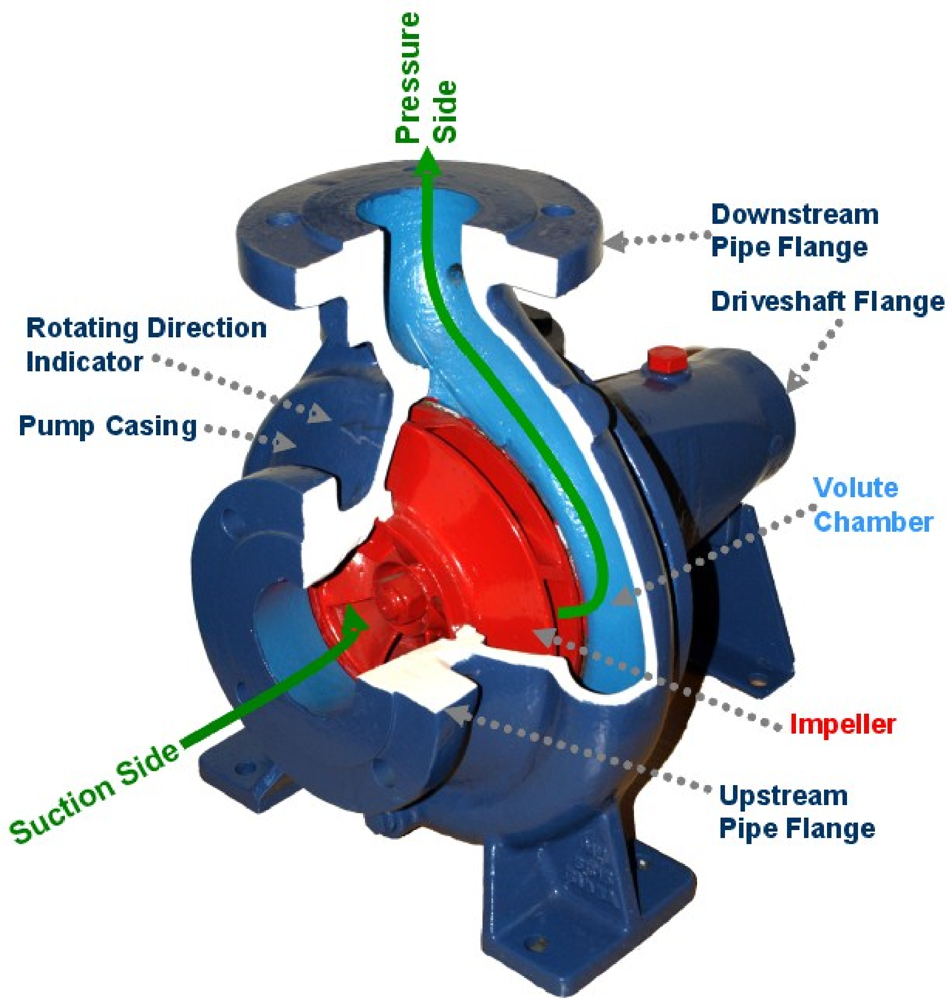


Figure 5 Example of a centrifugal pump with a direct connection for a PTO[18]

Figure 6 Sterling Engine 2, example of an elevated, centered pump panel

Figure 7 Sterling Engine 4, example of a driver's-side pump panel

2.6.3 Tank

Several types fire apparatus contain internal water tanks. These tanks vary in size depending upon the application, but are typically on the order of 200-300 gallons by requirement. In most, but not all, cases these tanks are directly connected to the water pump. The usual construction material for such tanks is plastic such as polypropylene. In some cases, manufacturers will use fiberglass for internal tanks. Most exterior tanks such as those used in tanker apparatus will be constructed of steel or stainless steel. Specific tank requirements can be found throughout Section 2.7 Standards and Development.

2.6.4 Hoses, Ladders, and Equipment

Hoses are a critical piece in the suppression of fires. Most all firefighting hose is of cloth reinforced rubber construction. Hoses are available in varying diameters ranging from one inch to as high as six inches. The construction of these hoses allows for them to be folded in a flat configuration, saving space on board the apparatus. Specific hose requirements can be found throughout Section 2.7 Standards and Development.

Ladders are used by firefighters to reach roofs and upper floors of structural fires. Generally, ladders are aluminum in construction. They can be of the folding or extension variety. In some cases, fire departments may choose fiberglass ladders as they offer a weight reduction. In some rare cases, such as the San Francisco Fire Department, ladders are constructed entirely of wood. This type of ladder is acceptable for use in fire suppressions as only particular varieties of wood are used. Usage of wooden ladders is predominately based upon tradition. Specific ladder requirements can be found throughout Section 2.7 Standards and Development.

NFPA standards require specific minimum configurations of equipment based upon the classification of the fire apparatus. Such equipment includes tools and safety devices such as the self-contained breathing apparatus (SCBA). Specific equipment requirements can be found throughout Section 2.7 Standards and Development.

2.6.5 Personnel Transport

The final responsibility of fire apparatus is transport of fire fighters. Most fire apparatus offer between two to six seats for firefighters. Specific safety requirements can be found in Section 2.7.10 Occupant/Firefighter Specifications on page 66.

2.7 Standards and Development

As previously stated, the selection and definition of US apparatus type is made using NFPA 1901, *Standard for Automotive Fire Apparatus, 2009 edition*. The seven classifications of fire apparatus defined in the document are as follows:

There is additional discussion of other types of fire apparatus as they are deemed pertinent to this report. These discussions are as follows

Standard NFPA language utilizes "specification wording," such as the word "shall," over others such as "must" or "has to." For the purposes of improved readability, these following descriptions will omit such language.

2.7.1 Pumper "Engine"

The most common fire apparatus in use today is the pumper. Commonly referred to as an engine, this vehicle is used to transport firefighters to and from the scene of the fire. More importantly, the apparatus provides the crucial role of pumping water, allowing the firefighters to live up to their moniker and fight the fire. Internal to these machines are high-capacity pumps that are fed by large, on-board water storage tank(s). Large bays are available for the storage of various size hoses, some of which are pre-connected to the pump. Lastly, additional compartments are provided around the apparatus for storage of critical equipment.

The minimum requirements for a pumper are defined in the fifth chapter of NFPA 1901, *Pumper Fire Apparatus*. An example pumper can be seen in Figure 8.

Figure 8 Sterling FD Engine 4, example of a pumper/engine

2.7.1.1 Pumping and Hose Specifications

An NFPA approved pumper must have a pump that has a minimum rated capacity of 750 gallons per minute (gpm). The on-board tank(s) must have a minimum capacity of 300 gallons. While this is the minimum, it is quite common for pumpers to exceed this minimum. Many have tanks sized at 500 gallons or even higher. With respect to fire hoses, the engine must accommodate the following in order to be NFPA certified:[19]

1. Storage requirements
    a. A minimum hose storage area of 30 ft^3 for 2½ in. diameter or larger hose, and
    b. A minimum of two bays to store pre-connected “hand lines”
        i. Hand lines must be 1½ in. diameter hose or larger
        ii. Each bay must have a volume of 3.5 ft^3 or larger
2. Supply hose requirements
    a. A minimum of 20 ft of “hard-walled” suction hose with strainer, or
    b. A minimum of 15 ft of “flexible” supply hose
3. Minimum hose requirements
    a. 800 ft (240 m) of 2½ in. (65 mm) or larger fire hose
    b. 400 ft (120 m) of 1½ in. (38 mm), 1¾ in. (45 mm), or 2 in. (52 mm) fire hose
4. Nozzle requirements
    a. One hand line nozzle, 200 gpm (750 L/min) minimum
    b. Two hand line nozzles, 95 gpm (360 L/min) minimum
    c. One play pipe with shutoff and 1 in. (25 mm), $1\frac{1}{8}$ in. (29 mm), and 1¼ in. (32 mm) tips

It is important to note that all of the hoses referenced above must conform to the applicable portions of NFPA 1961, *Standard on Fire Hose*.[20] Additionally, the nozzle requirements referenced above must conform to the applicable portions of NFPA 1964, *Standard for Spray Nozzles*.[21]

2.7.1.2 Equipment Specifications

Storage and quick accessibility to equipment is critical to the efficient usage of a pumper. An NFPA approved pumper must have a minimum 40 ft^3 of storage space for miscellaneous equipment. Required miscellaneous equipment is quoted verbatim as follows:[22]

> *(1) One 6 lb (2.7 kg) flathead axe mounted in a bracket fastened to the apparatus*
>
> *(2) One 6 lb (2.7 kg) pick-head axe mounted in a bracket fastened to the apparatus*
>
> *(3) One 6 ft (2 m) pike pole or plaster hook mounted in a bracket fastened to the apparatus*
>
> *(4) One 8 ft (2.4 m) or longer pike pole mounted in a bracket fastened to the apparatus*
>
> *(5) Two portable hand lights mounted in brackets fastened to the apparatus*
>
> *(6) One approved dry chemical portable fire extinguisher with a minimum 80-B:C rating mounted in a bracket fastened to the apparatus*

(7) One 2½ gal (9.5 L) or larger water extinguisher mounted in a bracket fastened to the apparatus

(8) One self-contained breathing apparatus (SCBA) complying with NFPA 1981, Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services, for each assigned seating position, but not fewer than four, mounted in brackets fastened to the apparatus or stored in containers supplied by the SCBA manufacturer

(9) One spare SCBA cylinder for each SCBA carried, each mounted in a bracket fastened to the apparatus or stored in a specially designed storage space

(10) One first aid kit

(11) Four combination spanner wrenches mounted in brackets fastened to the apparatus

(12) Two hydrant wrenches mounted in brackets fastened to the apparatus

(13) One double female 2½ in. (65 mm) adapter with National Hose (NH) threads, mounted in a bracket fastened to the apparatus

(14) One double male 2½ in. (65 mm) adapter with NH threads, mounted in a bracket fastened to the apparatus

(15) One rubber mallet, suitable for use on suction hose connections, mounted in a bracket fastened to the apparatus

(16) Two salvage covers each a minimum size of 12 ft × 14 ft (3.7 m × 4.3 m)

(17) Two or more wheel chocks, mounted in readily accessible locations, that together will hold the apparatus, when loaded to its GVWR or GCWR, on a

hard surface with a 20 percent grade with the transmission in neutral and the parking brake released

(18) One traffic vest for each seating position, each vest to comply with ANSI/ISEA 207, Standard for High-Visibility Public Safety Vests, and have a five-point breakaway feature that includes two at the shoulders, two at the sides, and one at the front

(19) Five fluorescent orange traffic cones not less than 28 in. (711 mm) in height, each equipped with a 6 in. (152 mm) retro-reflective white band no more than 4 in. (102 mm) from the top of the cone, and an additional 4 in. (102 mm) retro-reflective white band 2 in. (51 mm) below the 6 in. (152 mm) band

(20) Five illuminated warning devices such as highway flares, unless the five fluorescent orange traffic cones have illuminating capabilities

(21) One automatic external defibrillator (AED)

In addition to the required miscellaneous equipment, an NFPA approved pumper must carry a minimum of three types of ladders, including:[23]

- One straight ladder equipped with roof hooks
- One extension ladder
- One folding ladder

A roof ladder has specifically designed hooks that, when placed over the ridge of a roof, prevent the ladder from slipping. Stepladders and other types of multipurpose ladders can be substituted for the folder ladder provided that the replacement meets ANSI A14.2, *Ladders - Portable Metal - Safety Requirements*, or ANSI A14.5, *Ladders - Portable Reinforced Plastic - Safety Requirements*. In all cases, duty ratings of Type 1A or 1AA are required. Additional ladders are permitted provided that the meet the aforementioned ANSI criteria.

2.7.2 Initial Attack "Mini Pumper"

An initial attack fire apparatus is a reduced performance pumper. As the name suggests, it is specifically designed for initial response. This type of fire apparatus is routinely used by departments whose typical response is medical rather than structural (read fire). This type of vehicle offers fire suppression capabilities for environments that do not require high volume water application, such as car or dumpster fires. Thus the initial attack fire apparatus is generally used to reduce general wear and tear of the more expensive pumpers.

The minimum requirements for a pumper are defined in the sixth chapter of NFPA 1901, *Initial Attack Fire Apparatus*. An example initial attack fire apparatus can be seen in Figure 9.

Figure 9 Initial attack fire apparatus[24]

2.7.2.1 Pumping and Hose Specifications

An NFPA approved initial attack apparatus must have a pump that has a minimum rated capacity of 250 gpm. The on-board tank(s) must have a minimum capacity of 200 gallons. Additionally, the following must be accommodated:[25]

1. Storage requirements
    a. A minimum hose storage area of 10 ft^3 for 2½ in. diameter or larger hose, and
    b. A minimum of two bays to store pre-connected "hand lines"
        i. Hand lines must be 1½ in. diameter hose or larger
        ii. Each bay must have a volume of 3.5 ft^3 or larger
2. Supply hose requirements
    a. A minimum of 20 ft of "hard-walled" suction hose with strainer, or
    b. A minimum of 15 ft of "flexible" supply hose
3. Minimum hose requirements
    a. 300 ft (240 m) of 2½ in. (65 mm) or larger fire hose
    b. 400 ft (120 m) of 1½ in. (38 mm), 1¾ in. (45 mm), or 2 in. (52 mm) fire hose
4. Nozzle requirements
    a. Two hand line nozzles, 95 gpm (360 L/min) minimum

As with the pumper, all of the hoses referenced above must conform to the applicable portions of NFPA 1961, *Standard on Fire Hose*. Additionally, the nozzle requirements referenced above must conform to the applicable portions of NFPA 1964, *Standard for Spray Nozzles*.

2.7.2.2 Equipment Specifications

As with the pumper, storage and quick accessibility to equipment is critical to the efficient usage of an initial attack apparatus. An NFPA approval requires a minimum 22 ft^3 of storage space for miscellaneous equipment. Required miscellaneous equipment is quoted verbatim as follows:[26]

(1) One 6 lb (2.7 kg) pick-head axe mounted in a bracket fastened to the apparatus

(2) One 6 ft (2 m) pike pole or plaster hook mounted in a bracket fastened to the apparatus

(3) Two portable hand lights mounted in brackets fastened to the apparatus

(4) One approved dry chemical portable fire extinguisher with a minimum 80-B:C rating mounted in a bracket fastened to the apparatus

(5) One 2½ gal (9.5 L) or larger water extinguisher mounted in a bracket fastened to the apparatus

(6) One SCBA complying with NFPA 1981, Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services, for each assigned seating position, but not fewer than two, mounted in brackets fastened to the apparatus or stored in containers supplied by the SCBA manufacturer

(7) One spare SCBA cylinder for each SCBA carried, each mounted in a bracket fastened to the apparatus or stored in a specially designed storage space(s)

(8) One first aid kit

(9) Two combination spanner wrenches mounted in a bracket(s) fastened to the apparatus

(10) One hydrant wrench mounted in a bracket fastened to the apparatus

(11) One double female adapter, sized to fit 2½ in. (65 mm) or larger fire hose, mounted in a bracket fastened to the apparatus

(12) One double male adapter, sized to fit 2½ in. (65 mm) or larger fire hose, mounted in a bracket fastened to the apparatus

(13) One rubber mallet, for use on suction hose connections, mounted in a bracket fastened to the apparatus

(14) Two or more wheel chocks, mounted in readily accessible locations, that together will hold the apparatus, when loaded to its GVWR or GCWR, on a hard surface with a 20 percent grade with the transmission in neutral and the parking brake released

(15) One traffic vest for each seating position, each vest to comply with ANSI/ISEA 207, Standard for High-Visibility Public Safety Vests, and have a five-point breakaway feature that includes two at the shoulders, two at the sides, and one at the front

(16) Five fluorescent orange traffic cones not less than 28 in. (711 mm) in height, each equipped with a 6 in. (152 mm) retro-reflective white band no more than 4 in. (102 mm) from the top of the cone, and an additional 4 in. (102 mm) retro-reflective white band 2 in. (51 mm) below the 6 in. (152 mm) band

(17) Five illuminated warning devices such as highway flares, unless the five fluorescent orange traffic cones have illuminating capabilities

(18) One automatic external defibrillator (AED)

Lastly, an NFPA approved initial attack apparatus must carry a 12 ft or longer ground ladder. This ladder may be combination-type or an extension-type as required by the fire department. Additional ladders with duty ratings of Type 1A or 1AA under ANSI A14.2 or ANSI A14.5 are permitted.

2.7.3 Mobile Water Supply "Tanker"

A tanker is a type of apparatus that is designed to carry large quantities of water to a fire scene. This type of vehicle is commonly used in areas where inadequate hydrant coverage requires the use of tanker "shuttles" to ferry water to and from the source and the fire. An example of a tanker may be found in Figure 10.

Chapter 7 of NFPA 1901 governs the design of these types of apparatus. A tanker is required to carry a minimum of 1,000 gallons of water. It is not required to have a pump. This type of configuration is acceptable if the water source is a pressurized hydrant capable of filling the vehicle. In many cases (such as drafting water from a river or lake) this is not possible and the vehicle requires a pump. The minimum pumping capacity of such a pump is 250 gpm.

Figure 10 Tanker apparatus with a 1000 gallon (minimum) water tank[27]

2.7.3.1 Pumping and Hose Specifications

The on-board tank(s) of an NFPA approved tanker must have a minimum capacity of 1,000 gallons. If a fire department chooses to equip the tanker with a pump, a minimum of two pre-connected hoses are required With respect to fire hoses, the engine must accommodate the following in order to be NFPA certified:[28]

1. Storage requirements
    a. A minimum hose storage area of 6 ft^3 for 2½ in. diameter or larger hose
    b. A minimum of two bays to store pre-connected "hand lines" (*if pump-equipped*)
        i. Hand lines must be 1½ in. diameter hose or larger
        ii. Each bay must have a volume of 3.5 ft^3 or larger
2. Supply hose requirements
    a. A minimum of 20 ft of "hard-walled" suction hose with strainer, or
    b. A minimum of 15 ft of "flexible" supply hose
3. Minimum hose requirements
    a. 200 ft (240 m) of 2½ in. (65 mm) or larger fire hose
    b. 400 ft (120 m) of 1½ in. (38 mm), 1¾ in. (45 mm), or 2 in. (52 mm) fire hose
4. Nozzle requirements
    a. Two hand line nozzles, 95 gpm (360 L/min) minimum

As with the pumper, all of the hoses referenced above must conform to the applicable portions of NFPA 1961, *Standard on Fire Hose*. Additionally, the nozzle requirements referenced above must conform to the applicable portions of NFPA 1964, *Standard for Spray Nozzles*.

2.7.3.2 Equipment Specifications

An NFPA approved tanker must have a minimum 20 ft^3 of storage space for miscellaneous equipment. Required miscellaneous equipment is quoted verbatim as follows:[29]

(1) *One 6 lb (2.7 kg) flathead or pick-head axe mounted in a bracket fastened to the apparatus*

(2) *One 6 ft (2 m) or longer pike pole or plaster hook mounted in a bracket fastened to the apparatus*

(3) *Two portable hand lights mounted in brackets fastened to the apparatus*

(4) *One approved dry chemical portable fire extinguisher with a minimum 80-B:C rating mounted in a bracket fastened to the apparatus*

(5) *One 2½ gal (9.5 L) or larger water extinguisher mounted in a bracket fastened to the apparatus*

(6) *One SCBA complying with NFPA 1981, Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services, for each assigned seating position, but not fewer than two, mounted in brackets fastened to the apparatus or stored in containers supplied by the SCBA manufacturer*

(7) *One spare SCBA cylinder for each SCBA carried, each mounted in a bracket fastened to the apparatus or stored in a specially designed storage space(s)*

(8) *One first aid kit*

(9) *Two combination spanner wrenches mounted in a bracket fastened to the apparatus*

(10) One hydrant wrench mounted in a bracket fastened to the apparatus

(11) One double female adapter, sized to fit 2½ in. (65 mm) or larger fire hose, mounted in a bracket fastened to the apparatus

(12) One double male adapter, sized to fit 2½ in. (65 mm) or larger fire hose, mounted in a bracket fastened to the apparatus

(13) Two or more wheel chocks, mounted in readily accessible locations, that together will hold the apparatus, when loaded to its GVWR or GCWR, on a hard surface with a 20 percent grade with the transmission in neutral and the parking brake released

(14) One traffic vest for each seating position, each vest to comply with ANSI/ISEA 207, Standard for High-Visibility Public Safety Vests, and have a five-point breakaway feature that includes two at the shoulders, two at the sides, and one at the front

(15) Five fluorescent orange traffic cones not less than 28 in. (711 mm) in height, each equipped with a 6 in. (152 mm) retro-reflective white band no more than 4 in. (102 mm) from the top of the cone, and an additional 4 in. (102 mm) retro-reflective white band 2 in. (51 mm) below the 6 in. (152 mm) band

(16) Five illuminated warning devices such as highway flares, unless the five fluorescent orange traffic cones have illuminating capabilities

(17) One automatic external defibrillator (AED)

There are no ladder requirements for the tanker

2.7.4 Aerial/Ladder "Truck"

Chapter 8 of NFPA 1901 governs the requirements of an aerial apparatus. What is typically referred to as a "truck," the aerial employs an "aerial" feature that is hydraulically powered. Depending upon the configuration, these trucks may be simple extending ladders. Others may have baskets (or "towers") located at the end of the boom (refer to Figure 11). Some may be a tower on the end of an articulated boom (refer to Figure 14). Some are designed with pivot points located at the rear of the vehicle, while others are located behind the forward crew compartment. An aerial apparatus can be any combination of the preceding.

Figure 11 Example of a Tower Ladder[30]

2.7.4.1 Pumping and Hose Specifications

NFPA 1901 does not require a pump in aerial apparatus. They are, however, quite common. If the aerial apparatus is to be equipped with a pump, it must supply 250 gpm at a minimum. However, if it is intended to provide a permanently mounted waterway (a pipe extending the length of the ladder/boom to a dedicated monitor), a minimum of 1000 gpm is required. Thus there is a wide range of vibration possibilities with the pump of an aerial alone.

Unlike the pumper, there is no general requirement for a water tank in an aerial apparatus. Should a fire department decide to include a tank, there are requirements for the configuration, including baffles to provide stability while driving. These requirements can be found in Chapter 18 of NFPA 1901.

Lastly, unlike pumpers, it is a requirement that pump operators are not to be in contact with the ground. Note the pump operator standing on an extendable platform in Figure 11. This requirement is due to the electrocution risk posed by operating metal ladders in close proximity to power lines. There is a direct conduction path between the aerial device and the metal pipes at the pump. With rubber tires, the apparatus is likely insulated from the ground. Therefore the pump operator is at a significant risk of completing the circuit to ground while adjusting the metal control levers at the pump panel. NFPA 1901 requires the placement of signs warning pump operators of the hazard of electrocution.

With respect to fire hoses, the engine must accommodate the following in order to be NFPA certified:[31]

1. Storage requirements (*if a tank and a pump are installed*)
    a. There are no minimum hose storage area requirements
    b. A minimum of two bays to store pre-connected “hand lines”
        i. Hand lines must be 1½ in. diameter hose or larger
        ii. Each bay must have a volume of 3.5 ft^3 or larger
2. Supply hose requirements: N/A
3. Minimum hose requirements (*if not equipped with a pre-piped waterway*)
    a. Sufficient length(s) of 3 in. or larger attack hose to reach between the end of the ladder at full extension and the ground with 10 ft of slack hose
    b. One hose strap for each ladder section
4. Nozzle requirements (*at end of ladder*)
    a. 1¼ in. (32 mm), $1^3/_8$ in. (35 mm), or 1½ in. (38 mm) tips
    b. Control of end effectors
        i. Manually controlled tips require a halyard to direct the tips
        ii. Electrically controlled tips are permissible

As with the pumper, all of the hoses referenced above must conform to the applicable portions of NFPA 1961, *Standard on Fire Hose*. Additionally, the nozzle requirements referenced above must conform to the applicable portions of NFPA 1964, *Standard for Spray Nozzles*.

2.7.4.2 Equipment Specifications

An aerial apparatus is an equipment-intensive vehicle. With the exception of well-equipped rescue apparatus, the aerial generally contains the most equipment and ladders of any fire apparatus. An NFPA approved aerial must have a minimum 40 ft^3 of storage space for miscellaneous equipment. Required miscellaneous equipment is quoted verbatim as follows:[32]

(1) Two 6 lb (2.7 kg) flathead axes mounted in brackets fastened to the apparatus

(2) Three 6 lb (2.7 kg) pick-head axes mounted in brackets fastened to the apparatus

(3) Four pike poles mounted in brackets fastened to the apparatus

(4) Two 3 ft to 4 ft (1 m to 1.2 m) plaster hooks with D handles mounted in brackets fastened to the apparatus

(5) Two crowbars mounted in brackets fastened to the apparatus

(6) Two claw tools mounted in brackets fastened to the apparatus

(7) Two 12 lb (5 kg) sledgehammers mounted in brackets fastened to the apparatus

(8) Four portable hand lights mounted in brackets fastened to the apparatus

(9) One approved dry chemical portable fire extinguisher with a minimum 80-B:C rating mounted in a bracket fastened to the apparatus

(10) One 2½ gal (9.5 L) or larger water extinguisher mounted in a bracket fastened to the apparatus

(11) One SCBA complying with NFPA 1981, Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services, for each assigned seating position, but not fewer than four, mounted in brackets fastened to the apparatus or stored in containers supplied by the SCBA manufacturer

(12) One spare SCBA cylinder for each SCBA carried, each mounted in a bracket fastened to the apparatus or stored in a specially designed storage space(s)

(13) One first aid kit

(14) Six salvage covers, each a minimum size of 12 ft × 18 ft (3.6 m × 5.5 m)

(15) Four combination spanner wrenches mounted in brackets fastened to the apparatus

(16) Two scoop shovels mounted in brackets fastened to the apparatus

(17) One pair of bolt cutters, 24 in. (0.6 m) minimum, mounted in a bracket fastened to the apparatus

(18) Four ladder belts meeting the requirements of NFPA 1983, Standard on Life Safety Rope and Equipment for Emergency Services

(19) One 150 ft (45 m) light-use life safety rope meeting the requirements of NFPA 1983

(20) One 150 ft (45 m) general-use life safety rope meeting the requirements of NFPA 1983

(21) Two 150 ft (45 m) utility ropes having a breaking strength of at least 5000 lb (2300 kg)

(22) One box of tools to include the following:

a. One hacksaw with three blades

b. One keyhole saw

c. One 12 in. (0.3 m) pipe wrench

d. One 24 in. (0.6 m) pipe wrench

e. One ballpeen hammer

f. One pair of tin snips

g. One pair of pliers

h. One pair of lineman's pliers

i. Assorted types and sizes of screwdrivers

j. Assorted adjustable wrenches

k. Assorted combination wrenches

(23) Two or more wheel chocks, mounted in readily accessible locations, that together will hold the apparatus, when loaded to its GVWR or GCWR, on a hard surface with a 20 percent grade with the transmission in neutral and the parking brake released

(24) One traffic vest for each seating position, each vest to comply with ANSI/ISEA 207, Standard for High-Visibility Public Safety Vests, and have a five-point breakaway feature that includes two at the shoulders, two at the sides, and one at the front

(25) Five fluorescent orange traffic cones not less than 28 in. (711 mm) in height, each equipped with a 6 in. (152 mm) retro-reflective white band no more

than 4 in. (102 mm) from the top of the cone, and an additional 4 in. (102 mm) retro-reflective white band 2 in. (51 mm) below the 6 in. (152 mm) band

(26) Five illuminated warning devices such as highway flares, unless the five fluorescent orange traffic cones have illuminating capabilities

(27) One automatic external defibrillator (AED)

In addition to the required miscellaneous equipment, an NFPA approved aerial must carry the following ladder configurations:[33]

- A minimum of 115 ft of fire department ground ladders
- Two straight ladders equipped with folding roof hooks
- Two extension ladders
- One folding ladder

Stepladders and other types of multipurpose ladders can be substituted for the folder ladder provided that the replacement meets ANSI A14.2 or ANSI A14.5. In all cases, duty ratings of Type 1A or 1AA are required. Additional ladders are permitted provided that the meet the aforementioned ANSI criteria.

2.7.5 Quint Fire Apparatus

Chapter 9 of NFPA 1901 governs the requirements of a quint apparatus. The etymology of the term quint refers to the five functions that the apparatus performs.[34] The functions as well as a matrix comparison to the pumper and aerial minimum requirements are presented in Table 7.

Table 7 Five-function minimum requirements of common apparatus

	Pumper	Tanker	Aerial	Quint	Special
Aerial device			X	X	
Fire pump	X			X	
Tank	X	X		X	
Hose	X	X		X	
Ground ladders	X		X	X	

As the image of a quint appears very much the same as that of an aerial apparatus, no figure will be presented here. Instead, please refer to Figure 11 for a representative picture of a quint. In all actuality, the apparatus in Figure 11 could very well be a quint, considering the large number of outlet ports indicated by the pump panel.

One of the chief reasons for the deployment of a quint is functionality. In particular, this vehicle offers all of the advantages of an aerial with that of a pumper with an increased pump capacity of 1,000 gpm from 750 gpm. This type of apparatus allows a smaller or minimally staffed department to deploy both a pumper and an aerial with a minimal number of firefighters. The negative of such a vehicle is the size. This apparatus can be seen as (1) a very large pumper or (2) an aerial weighed down with a pump, hoses, and an on-board water tank.

As with the aerial apparatus, NFPA 1901 requires that pump operators are not to be in contact with the ground. Additionally, there is a requirement that signs warning pump operators of the hazard of electrocution be placed near the pump panel.

2.7.5.1 Pumping and Hose Specifications

An NFPA approved quint must have a pump that has a minimum rated capacity of 1,000 gpm. The on-board tank(s) must have a minimum capacity of 300 gallons. With respect to fire hoses, the quint must accommodate the following in order to be NFPA certified:[35]

1. Storage requirements
    a. A minimum hose storage area of 30 ft^3 for 2½ in. diameter or larger hose, and
    b. A minimum of two bays to store pre-connected "hand lines"
        i. Hand lines must be 1½ in. diameter hose or larger
        ii. Each bay must have a volume of 3.5 ft^3 or larger
2. Supply hose requirements
    a. A minimum of 20 ft of "hard-walled" suction hose with strainer, or
    b. A minimum of 15 ft of "flexible" supply hose
3. Minimum hose requirements
    a. 800 ft (240 m) of 2½ in. (65 mm) or larger fire hose
    b. 400 ft (120 m) of 1½ in. (38 mm), 1¾ in. (45 mm), or 2 in. (52 mm) fire hose
4. Nozzle requirements
    a. One hand line nozzle, 200 gpm (750 L/min) minimum
    b. Two hand line nozzles, 95 gpm (360 L/min) minimum

c. One play pipe with shutoff and 1 in. (25 mm), $1\frac{1}{8}$ in. (29 mm), and 1¼ in. (32 mm) tips

As with previous apparatus, all of the hoses referenced above must conform to the applicable portions of NFPA 1961, *Standard on Fire Hose*. Additionally, the nozzle requirements referenced above must conform to the applicable portions of NFPA 1964, *Standard for Spray Nozzles*.

2.7.5.2 Equipment Specifications

As with the aerial, a quint apparatus is an equipment-intensive vehicle. An NFPA approved quint must have a minimum 40 ft^3 of storage space for miscellaneous equipment. Required miscellaneous equipment is quoted verbatim as follows:[36]

(1) One 6 lb (2.7 kg) flathead axe mounted in a bracket fastened to the apparatus

(2) One 6 lb (2.7 kg) pick-head axe mounted in a bracket fastened to the apparatus

(3) One 6 ft (2 m) pike pole or plaster hook mounted in a bracket fastened to the apparatus

(4) One 8 ft (2.4 m) or longer pike pole mounted in a bracket fastened to the apparatus

(5) Two portable hand lights mounted in brackets fastened to the apparatus

(6) One approved dry chemical portable fire extinguisher with a minimum 80-B:C rating mounted in a bracket fastened to the apparatus

(7) One 2½ gal (9.5 L) or larger water extinguisher mounted in a bracket fastened to the apparatus

(8) One SCBA complying with NFPA 1981, Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services, for each assigned seating position, but not fewer than four, mounted in brackets fastened to the apparatus or stored in containers supplied by the SCBA manufacturer

(9) One spare SCBA cylinder for each SCBA carried, each mounted in a bracket fastened to the apparatus or stored in a specially designed storage space(s)

(10) One spare SCBA cylinder for each SCBA carried

(11) One first aid kit

(12) Four combination spanner wrenches mounted in brackets fastened to the apparatus

(13) Two hydrant wrenches mounted in brackets fastened to the apparatus

(14) One double female 2½ in. (65 mm) adapter with National Hose (NH) threads, mounted in a bracket fastened to the apparatus

(15) One double male 2½ in. (65 mm) adapter with NH threads, mounted in a bracket fastened to the apparatus

(16) One rubber mallet, for use on suction hose connections, mounted in a bracket fastened to the apparatus

(17) Four salvage covers, each a minimum size of 12 ft × 14 ft (3.7 m × 4.3 m)

(18) Four ladder belts meeting the requirements of NFPA 1983, Standard on Life Safety Rope and Equipment for Emergency Services

(19) One 150 ft (45 m) light-use life safety rope meeting the requirements of NFPA 1983

(20) One 150 ft (45 m) general-use life safety rope meeting the requirements of NFPA 1983

(21) Two or more wheel chocks, mounted in readily accessible locations, that together will hold the apparatus, when loaded to its GVWR or GCWR, on a hard surface with a 20 percent grade with the transmission in neutral and the parking brake released

(22) One traffic vest for each seating position, each vest to comply with ANSI/ISEA 207, Standard for High-Visibility Public Safety Vests, and have a five-point breakaway feature that includes two at the shoulders, two at the sides, and one at the front

(23) Five fluorescent orange traffic cones not less than 28 in. (711 mm) in height, each equipped with a 6 in. (152 mm) retro-reflective white band no more than 4 in. (102 mm) from the top of the cone, and an additional 4 in. (102 mm) retro-reflective white band 2 in. (51 mm) below the 6 in. (152 mm) band

(24) Five illuminated warning devices such as highway flares, unless the five fluorescent orange traffic cones have illuminating capabilities

(25) One automatic external defibrillator (AED)

In addition to the required miscellaneous equipment, an NFPA approved quint apparatus must carry the following ladder configurations:[37]

- A minimum of 85 ft of fire department ground ladders
- One straight ladder equipped with folding roof hooks
- One extension ladder
- One folding ladder

Stepladders and other types of multipurpose ladders can be substituted for the folder ladder provided that the replacement meets ANSI A14.2 or ANSI A14.5. In all cases, duty ratings of Type 1A or 1AA are required. Additional ladders are permitted provided that the meet the aforementioned ANSI criteria.

2.7.6 Special Service Fire Apparatus

The Special Service Fire Apparatus can be considered the "other" category of fire apparatus. This can include such activities as vehicle extraction, hazardous materials operations, dive/water rescue, or even collapse rescue (for FEMA Teams).

For the purposes of this investigation, the particulars of this category will be curtailed towards the classic "rescue" vehicle. A specific definition of a rescue apparatus will differ between various fire departments; however, the main idea is that it serves as a platform to supply the equipment necessary for "rescue" operations.

As with the aerial apparatus, there are no general requirements for water tanks and/or pumps. Some fire departments co-habit pumpers with vehicle rescue operations, as a small amount of water may be necessary to quench a vehicle fire, or at least guard against the potential. In these cases a minimum capacity of 250 gpm is required. For the most part, rescue vehicles do not have pumps or tanks. An example of a rescue apparatus without a pump or a water tank can be found in Figure 12.

These vehicles do have the tendency to have very heavy equipment installed. Additional generators are present for hydraulic tools. Many vehicle-rescue units also carry large amount of wooden cribbing to stabilize vehicles during extraction. The vibration dynamics of these types of apparatus may vary from that of pumping operations, but these vehicles can still be exceedingly heavy and prone to road vibration.

Governing NFPA language can be found in Chapter 10 of NFPA 1901.

Figure 12 Broomall Rescue 53, example of a rescue apparatus without pump or tank

2.7.6.1 Equipment Specifications

An NFPA approved special service fire apparatus must have a minimum 120 ft^3 of storage space for miscellaneous equipment. Required miscellaneous equipment is quoted verbatim as follows:[38]

(1) Two portable hand lights mounted in brackets fastened to the apparatus

(2) One approved dry chemical portable fire extinguisher with a minimum 80-B:C rating mounted in a bracket fastened to the apparatus

(3) One 2½ gal (9.5 L) or larger water extinguisher mounted in a bracket fastened to the apparatus

(4) One SCBA complying with NFPA 1981, Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services, for each assigned seating position, but not fewer than two, mounted in brackets fastened to the apparatus or stored in containers supplied by the SCBA manufacturer

(5) One spare SCBA cylinder for each SCBA carried, each mounted in a bracket fastened to the apparatus or stored in a specially designed storage space(s)

(6) One first aid kit

(7) Two or more wheel chocks, mounted in readily accessible locations, that together will hold the apparatus, when loaded to its GVWR or GCWR, on a hard surface with a 20 percent grade with the transmission in neutral and the parking brake released

(8) One traffic vest for each seating position, each vest to comply with ANSI/ISEA 207, Standard for High-Visibility Public Safety Vests, and have a five-point breakaway feature that includes two at the shoulders, two at the sides, and one at the front

(9) Five fluorescent orange traffic cones not less than 28 in. (711 mm) in height, each equipped with a 6 in. (152 mm) retro-reflective white band no more than 4 in. (102 mm) from the top of the cone, and an additional 4 in. (102 mm) retro-reflective white band 2 in. (51 mm) below the 6 in. (152 mm) band

(10) Five illuminated warning devices such as highway flares, unless the five fluorescent orange traffic cones have illuminating capabilities

(11) One automatic external defibrillator (AED)

There is no particular requirement for ladders in a special service apparatus. If ladders are supplied they must meet NFPA 1931, *Standard for Manufacturer's Design of Fire Department Ground Ladders,* ANSI A14.2, or ANSI A14.5. In cases using ANSI certifications, duty ratings of Type 1A or 1AA are required.

2.7.7 Mobile Foam Fire Apparatus

A mobile foam fire apparatus is a vehicle that is designed to fight fires using foam. Many of the requirements are similar to that of the pumper. If the apparatus is to employ an aerial feature, it is required to have a pre-piped water way, but is not required to have the larger pumping capability required of an aerial. As this vehicle can look similar to any of the other classifications, an image of such will not be included.

2.7.7.1 Pumping and Hose Specifications

An NFPA approved mobile foam fire apparatus must have a pump that has a minimum rated capacity of 750 gpm. The on-board tank(s) must have a minimum capacity of 500 gallons for foam concentrate. Additionally, there must be a foam proportioning system which correctly proportions the foam concentrate with water. With respect to fire hoses, the apparatus must accommodate the following in order to be NFPA certified:[39]

1. Storage requirements
    a. A minimum hose storage area of 30 ft^3 for 2½ in. diameter or larger hose, and
    b. A minimum of two bays to store pre-connected "hand lines"
        i. Hand lines must be 1½ in. diameter hose or larger
        ii. Each bay must have a volume of 3.5 ft^3 or larger
2. Supply hose requirements
    a. A minimum of 20 ft of "hard-walled" suction hose with strainer, or
    b. A minimum of 15 ft of "flexible" supply hose

3. Minimum hose requirements
    a. 800 ft (240 m) of 2½ in. (65 mm) or larger fire hose
    b. 400 ft (120 m) of 1½ in. (38 mm), 1¾ in. (45 mm), or 2 in. (52 mm) fire hose
4. Nozzle requirements
    a. Four foam or water hand-line nozzles, 200 gpm (750 L/min) minimum
    b. Two foam or water hand-line nozzles, 95 gpm (360 L/min) minimum
    c. One pre-connected monitor, rated to discharge a minimum of 1000 gpm (4000 L/min), mounted on top of the fire apparatus with a spray or foam nozzle rated at a minimum of 1000 gpm (4000 L/min)

As with previous apparatus, all of the hoses referenced above must conform to the applicable portions of NFPA 1961, *Standard on Fire Hose*. Additionally, the nozzle requirements referenced above must conform to the applicable portions of NFPA 1964, *Standard for Spray Nozzles*.

2.7.7.2 Equipment Specifications

An NFPA approved mobile foam fire apparatus must have a minimum 40 ft^3 of storage space for miscellaneous equipment. Required miscellaneous equipment is quoted verbatim as follows:[40]

(1) One 6 lb (2.7 kg) pick-head axe mounted in a bracket fastened to the apparatus

(2) One 6 ft (2 m) pike pole or plaster hook mounted in a bracket fastened to the apparatus

(3) Two portable hand lights mounted in brackets fastened to the apparatus

(4) One approved dry chemical portable fire extinguisher with a minimum 80-B:C rating mounted in a bracket fastened to the apparatus

(5) One SCBA complying with NFPA 1981, Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services, for each assigned seating position, but not fewer than four, mounted in brackets fastened to the apparatus or stored in containers supplied by the SCBA manufacturer

(6) One spare SCBA cylinder for each SCBA carried, each mounted in a bracket fastened to the apparatus or stored in a specially designed storage space

(7) One first aid kit

(8) Four combination spanner wrenches mounted in brackets fastened to the apparatus

(9) Two hydrant wrenches mounted in brackets fastened to the apparatus

(10) One double female 2½ in. (65 mm) adapter with National Hose (NH) threads, mounted in a bracket fastened to the apparatus

(11) One double male 2½ in. (65 mm) adapter with NH threads, mounted in a bracket fastened to the apparatus

(12) One rubber mallet, suitable for use on suction hose connections, mounted in a bracket fastened to the apparatus

(13) Two or more wheel chocks, mounted in readily accessible locations, that together will hold the apparatus, when loaded to its GVWR or GCWR, on a

hard surface with a 20 percent grade with the transmission in neutral and the parking brake released

(14) One traffic vest for each seating position, each vest to comply with ANSI/ISEA 207, Standard for High-Visibility Public Safety Vests, and have a five-point breakaway feature that includes two at the shoulders, two at the sides, and one at the front

(15) Five fluorescent orange traffic cones not less than 28 in. (711 mm) in height, each equipped with a 6 in. (152 mm) retro-reflective white band no more than 4 in. (102 mm) from the top of the cone, and an additional 4 in. (102 mm) retro-reflective white band 2 in. (51 mm) below the 6 in. (152 mm) band

(16) Five illuminated warning devices such as highway flares, unless the five fluorescent orange traffic cones have illuminating capabilities

(17) One automatic external defibrillator (AED)

There are no ladder requirements for the mobile foam fire apparatus.

2.7.8 Squad

The role fulfilled by a squad apparatus is that of personnel and equipment transport. These vehicles are typically common sport utility vehicles (refer to Figure 13). This type of apparatus is somewhat discussed with NFPA 1901 in the sense that crew compartment safety issues, such as SCBA containment, are discussed. For the most part, being common civilian vehicles, they have already undergone rigorous safety testing.

An additional function provided by some squads is brush/wildland firefighting. Discussed specifically in NFPA 1906[41], these types of vehicles have limited pump capacity when compared to the significantly larger pumpers defined by NFPA 1901.

Figure 13 Squad apparatus shown with brush firefighting capability[42]

2.7.9 Other Types of Apparatus

Additional types of vehicles are used by departments but were not considered for inclusion in the testing. These types of vehicles may be less-common combinations of the above types or they may be application specific vehicles.

An example of a combination vehicle would be the snorkel truck (refer to Figure 14). The snorkel is loosely defined as a cross between a pumper and an aerial truck. It employs a hydraulically powered, articulated and extendable boom, which in most cases will have reduced reach as compared to a typical ladder truck. In many cases, though, these apparatus have pumps with capacities that are larger than 250 gpm. Thus the question arises: under which type of vehicle should the snorkel be classified?

Figure 14 Example of a snorkel engine; combination pumper and truck[43]

Careful attention would need to be paid to the snorkel as it would be easy to consider it an aerial apparatus with a moderate (greater than 250 gpm) pump. However, this would be a mistake. NFPA 1901 specifically addresses apparatus that fall into the snorkel category. Chapter 8 provides the distinction:

> *8.1.1 If the apparatus is to function as an aerial fire apparatus, it shall meet the requirements of this chapter.*
>
> *8.1.2 If the apparatus is to function as a pumper with an aerial device, it shall meet all the requirements of Chapter 5 instead of Chapter 8.*

Thus proper classification would depend upon the functionality of the apparatus. If aerial operation was predominating, it would be an aerial, and vice versa. While this may seem trivial, recall Section 2.7.4 Aerial/Ladder "Truck, the aerial does not require a particular tank size and can operate with a smaller pump. The dynamics of such a vehicle would be greatly different than those of a pumper/engine.

An example of a highly specialized piece of equipment would be the Aircraft Rescue Fire Fighting (ARFF) truck (refer to Figure 15). Designed to be self-sufficient, this vehicle internally carries all the water and firefighting foam additive that would be reasonably required at a given aircraft crash site. In the process of providing support to crashed aircraft the immediate priority is in providing cooling water and/or foam directly to the aircraft in an effort to buy victims time to evacuate. Some of these vehicles employ boom penetration nozzles which directly pierce the hull of the aircraft. This allows the delivery of a fog stream throughout the interior of the cabin, which greatly reduces the lethal heat enveloping the evacuating survivors.

Figure 15 Example of a DFW Airport Oshkosh crash truck with a boom penetration nozzle[44]

2.7.10 Occupant/Firefighter Specifications

Chapter 14 of NFPA 1901 provides specifications regarding the safety of occupants while operating the pumper. Required federal and regulatory standards of crash worthiness are specified. Requirements for the securing of equipment are defined. Finally, escape and means of egress are defined with respect to the survivability of the occupants.

Specification 14.1.10, titled "SCBA Mounting" specifically defines the mounting of a self-contained breathing apparatus (SCBA). An SCBA is the source of fresh breathing air for a firefighter inside a burning structure. An example of an SCBA is provided in Figure 16 on page 67.

The secure method of mounting an SCBA in a pumper generally leads to good conduction of vibrations. Two particular sections are worthy of note,

> *14.1.10.1 Where SCBA units are mounted within a driving or crew compartment, a positive latching mechanical means of holding the SCBA device in its stowed position shall be provided such that the SCBA unit cannot be retained in the mount unless the positive latch is engaged.*
>
> *14.1.10.2 The bracket holding device and its mounting shall retain the SCBA unit when subjected to a 9 G force and shall be installed in accordance with the bracket manufacturer's requirements.*[45]

A more in-depth discussion of the SCBA and the effects of vibration can be found in Section 2.7.11 The Self Contained Breathing Apparatus which can be found on page 67.

2.7.11 The Self Contained Breathing Apparatus

As previously mentioned in Section 2.7.10 Occupant/Firefighter Specifications, the self-contained Breathing Apparatus is the firefighter's supply of fresh breathing air while fighting a fire. An example of an SCBA may be found in Figure 16. The circled portions of the image show a standard version of the Pathfinder locator system co-invented by this author that has been installed in the Sperian/Honeywell Warrior SCBA.

Figure 16 Example of an SCBA with author's firefighter locator installed (circled)[46]

It is an every day, common practice for fire departments to utilize apparatus seats that retain an SCBA (refer to Figure 17). The logic is simple; it allows a firefighter to don his/her gear while en route to a scene. It should also be noted that NFPA 1901 requires certain numbers of SCBAs to be available for use by firefighters in every class of apparatus described in the previous apparatus type discussion. In is an almost certainty that an SCBA would be located somewhere in the crew compartment of *every* piece of fire apparatus in the country (emphasis added).

Figure 17 Typical seat-mounted SCBA brackets[47]

The Chassis Subcommittee of the Fire Apparatus Manufacturer's Association Technical Committee conducted an anthropometric study of firefighter physiology and equipment statistics. A condensed version of the data pertaining to SCBAs can be found below.

Table 8 Statistical weight data for SCBAs[48]

	5th Pct.	50th Pct.	95th Pct.	Avg.	Std. Dev.	Median	Min	Max
SCBA Weight (lb)	17	27	30	26	4	27	13	47

Recall that section 14.1.10.2 requires any SCBA contained within a crew compartment to be secured in such a manner as to withstand a 9g loading.[49] It is this particular wording that leads designers to create brackets that rigidly mount the SCBAs. Given a maximum possible weight of 47 pounds, any given bracket may be required to withstand a minimum of 423 pounds of force. With design factors of safety, it is virtually guaranteed that SCBA mounts will be rigid and thus likely to couple vibration energy from the vehicle.

The level of protection afforded by NFPA 1901 has grown over the years. The most recent revision dates of the document are 2009 (current), 2003, 1999, 1996, and 1991. In less than eighteen years, there have been five revisions of the document, averaging 3.6 years per revision. For comparison, NFPA standards for electronic safety equipment (which arguably evolve faster than a vehicle) typically revise only every five to six years. Many of the changes in NFPA 1901 have been for improvements to vehicle safety.

Changes in crash worthiness have resulted in increasingly complex SCBA retention methods. An example of such a trend is shown below in Figure 18. The vibration damping afforded by the thin, dipped urethane scratch guards is minimal at best. These all metal brackets come in direct contact with not only the SCBA, but more importantly it's more fragile electronics. Therefore it is really not much of a surprise that vibration damage is occurring to SCBA electronics.

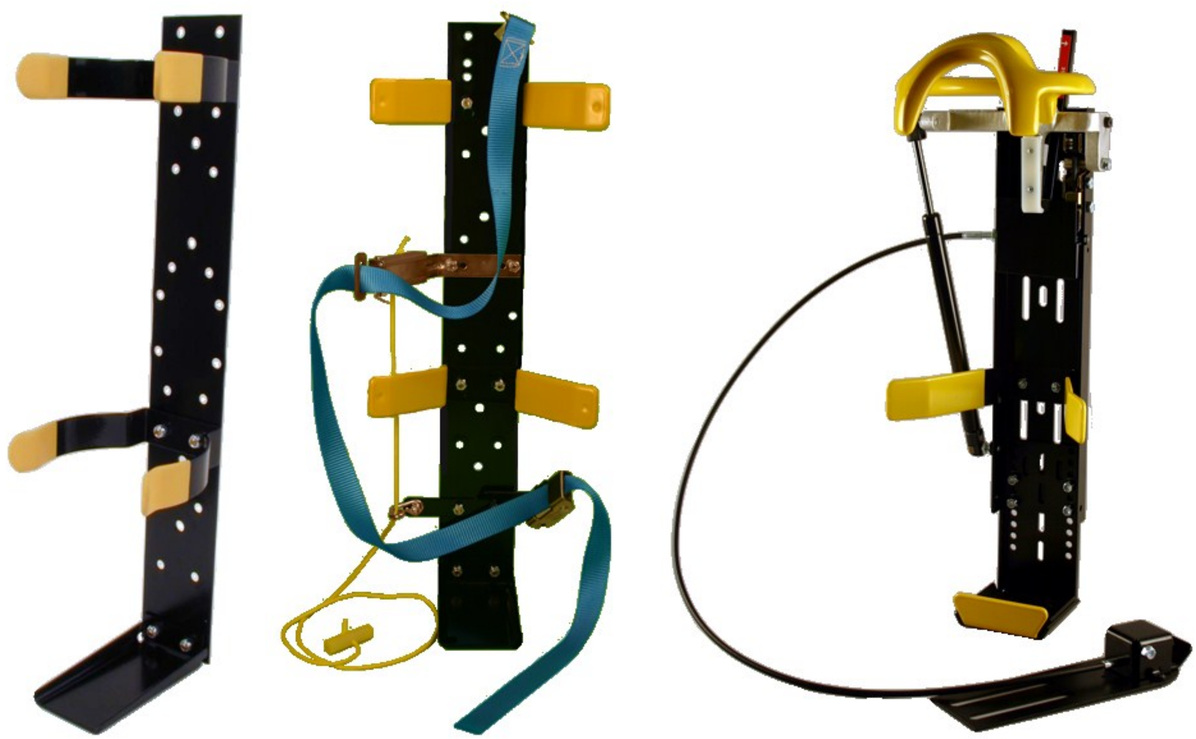


Figure 18 Examples of SCBA brackets showing increasing complexity left to right[50]

2.8 Vibration

At this point, there is very little documentation into the effects of vibrations upon equipment and upon firefighters. The observed effects of vibrations on equipment are the justification of this investigation.

The effects of vibration on firefighters are somewhat outside the scope of this research. While germane to the subject of vibration, the focus of this effort is on equipment damage. For thoroughness, however, a brief observation of the risk to firefighters is presented below.

2.8.1 Vibration Impact on Firefighters

Specific information regarding firefighters and vehicle vibration is virtually non-existent. A study of Italian bus drivers may provide insight to the effects of whole body vibrations on firefighters. Typical busses are comparable in size and weight to that of pumpers. Usually these vehicles are close to the maximum length for single unit vehicles and can max out in gross vehicle weight.

One of the tests of the study involved determining the prevalence of back related pain and injury issues of bus drivers with that of non-driver control individuals. The results of the test can be seen in Table 9 on the following page. It is clear from the data that there are increased odds ratios that bus drivers subjected to whole body vibrations will experience lower back pain and problems when compared to non-driving individuals.

Extrapolation of these bus-based results to firefighters may not be applicable as the dynamics of the vehicles are somewhat different. However, it should be noted that the vehicles are similar in dimensions and weight. Thus there may be legitimate concern that firefighters are being exposed to damaging vibration.

Table 9 Odds ratios (OR) for lower back pain in bus drivers compared to controls[51]

	Bus Drivers		Controls		
Complaints	n	%	n	%	OR* (95% CI)†
Low back symptoms					
Lifetime prevalence	196	83.8	83	66.4	3.12 (1.82-5.34)
12-Month prevalence	194	82.9	82	65.6	2.99 (1.75-5.09)
7-Day prevalence	146	62.4	57	45.6	2.35 (1.47-3.76)
Sciatic pain	76	32.5	27	21.6	1.95 (1.15-3.31)
Acute LBP	82	35	30	24	1.88 (1.13-3.14)
LBP	93	39.7	25	20	2.57 (1.52-4.35)
Chronic LBP	113	48.3	37	29.6	2.36 (1.46-3.81)
Treated LBP	142	60.7	62	50	1.89 (1.19-3.02)
Disc protrusion‡	19	8.1	9	7.2	1.28 (0.55-2.99)

* Odds ratios are adjusted for age, body mass index, education, sport activity, smoking, marital status, mental trauma, postural load, and previous jobs at risk for LBP by logistic modeling.

† 95% Confidence Intervals (CI) for Low Back Symptoms and Low Back Pain (LBP)

‡ Adjusted for age, back trauma, postural load, and previous jobs at risk for LBP.

2.8.2 Vibration Types

Pumping operations was the focus of this investigation. As detailed in Section 2.6.2 Pumping, a large portion of the expected vibration subjected upon a pumper is that of pumping. Movement of large quantities of water through the centrifugal pump is likely to induce vibrations in the apparatus. As the engine is directly coupled to the pump through a transmission, these vibrations may be due to either the engine or the pump. These vibrations are likely to be unvarying in frequency while pumping at a constant volumetric rate.

Similar to pumping, any machinery mounted to the chassis of a fire apparatus is likely to induce vibrations. Section 3.5.1.5 Engine 2 Type (c) Test on page 190 shows the tests of Sterling Fire Department Engine 2 and the auxiliary power generator that is mounted in the cabinet. In this case, the noisy generator shakes considerably further adding to the vibration environment.

Road noise and jostling is an additional source of vibration. The results of Paul Cotnoir's thesis research indicate that the effect of road vibration can contribute as much as 0.1 g of acceleration to an ambulance.[52] The dynamics of a small ambulance compared to a 54,000 lb pumper are not necessarily comparable. It is likely that the suspension of the pumper apparatus is significantly stiffer than that of an ambulance. Thus it may be expected that the transient effects of road vibration may be more significant.

CHAPTER 3: Vibration Characterization

3.1 Introduction

The objective of this Major Qualifying Project was to characterize the vibrational environment of pumper operations. The motivation for this characterization was the occurrence of irreparable damage to mission critical firefighting electronics due to vibration exposure while on pumper apparatus.

To collect the vibrational data of modern fire apparatus, a purpose-built, novel sensor was developed. A front-end recording virtual instrument was developed using the National Instruments LabView suite. A second virtual instrument was designed to normalize the data to standard gravity and to characterize its spectral content. The sensor was then baseline calibrated and subsequently validated.

Data was collected on two separate pumper apparatus at a test with the Sterling Fire Department on 04/18/2012. Post analysis of this data was performed and is included herein.

Specifics of the solution process are detailed in Section 3.2 Solution Process.

3.2 Solution Process

The characterization of vibrations in fire apparatus was accomplished using a four part process broken into sub-tasks as follows:

1. Experimental planning (page 76)
    a. Identify data collection methodology (page 78)
    b. Specify and/or design necessary equipment for data collection (page 80)
    c. Fabricate necessary equipment (page 83)
    d. Design and implement instrumentation for the equipment (page 87)
    e. Calibrate instrumentation and equipment (page 100)
    f. Baseline noise characterization (page 102)
    g. Validate instrument and equipment prior to fire department testing (page 106)
2. Data collection (page 109)
    a. Location type and positioning of sensor (page 110)
    b. Specific test data (page 113)
3. Data analysis (page 147)
    a. Spectral transformations (page 147)
    b. Summary of results (page 208)
4. Results and NFPA standards (page 212)

3.3 Experimental Planning

One of the most important aspects of collecting data is proper sensor choice. Understanding the signal characteristics is critical to determining the sensitivity window of the sensor. For the purposes of this Major Qualifying Project the focus of the tests was upon engine- and pump-induced vibrations in a stationary pumper.

Recall from Section 2.6.2 Pumping on page 19, that a typical centrifugal pump requires approximately 3,500 rpm to attain the required volume and pressure levels of an NFPA 1901 pumper apparatus. The typical diesel engine operating speeds for these types of trucks therefore necessitate pump transmissions with ratios on the order of 2.25 to 1. Using these ratios and estimated engine velocities, a set of frequencies can be identified for study. Table 10 roughly outlines the expected frequencies of expected vibration based upon engine speed and anticipated pump speed. The engine speeds observed during fire suppression pumping operations can vary dramatically. This is to be expected as the volumetric flow rate of the centrifugal pump is proportional to its speed. The more water being demanded, the higher the pump operator has to set the throttle. Thus vibration content in the frequencies listed should be expected.

Additional preliminary sensor design considerations for the vibration sensor were taken from the Ph.D. research work of Paul Cotnoir on the effects of vibration on comfort, care and safety of ambulance patients. A synopsis of the work found on the WPI Mechanical Engineering Department website, Materials Science and Engineering section, identified that the chief vibrations observed in an ambulance were in the range of 1 to 6 Hz. The amplitudes of these vibrations ranged from 0.46 to 2.55 m/sec^2, or 0.05 to 0.26 g's when normalized to standard gravity. These amplitudes were observed during travel over four different types of road surfaces, at three different speeds.[53]

Table 10 Expected frequency content for a standard pumper

Engine [RPM]	Engine [Hz]	Pump [Hz]	Comments
750	13	28	Typical idle for Sterling FD Engines 2 and 4
1,000	17	38	
1,100	18	41	Maximum observed engine rpm at Sterling FD test
1,250	21	47	
1,500	25	56	
1,700	28	64	Maximum expected per Waterous[54]

Many box-style ambulances have maximum engine speeds around 3500 to 4000 rpm. These numbers would suggest that engine-induced vibrations would roughly be on the order of 58 to 67 Hz. As the research of Cotnoir identifies the dominating terms between 1 to 6 Hz, it can safely be assumed that these vibrations are due to road conditions. However, this does not indicate that the engine and pump induced vibrations of a fire apparatus should be ignored. Furthermore, the significant difference in mass between an ambulance and fire apparatus suggests that the dynamics of the apparatus may very well be more energetic.

3.3.1 Data Collection Methodology

The sheer volume of data necessary to characterize the vibration in all apparatus under all conditions is a daunting task. Characterization of damage to SCBAs, at a minimum, should include measurements in locations where the equipment would be located. However, SCBAs are not the only pieces of equipment subjected to the vibration. Long term wear and vibration damage to the pumps and chassis might be considered. Even issues of driver and passenger comfort might be explored. An example matrix of potential vibration measurements for differing apparatus and operating conditions can be seen in Table 11. The legend at the bottom of the table identifies the four quadrants of a given cell. The cells highlighted in green denote types of data that were collected during the Sterling Fire Department test described later.

Table 11 Matrix of potential vibration conditions for most common apparatus

	Pumper		Aerial		Quint		Rescue		Rescue w/pump		Tanker		Squad	
Idle	x	x	x	x	x	x	x		x	x	x	x	x	x
	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Pumping	x	x	x	x	x	x			x	x	x	x	x	x
	x	x	x	x	x	x			x	x	x	x	x	x
15 mph asphalt	x		x		x		x		x		x		x	
	x	x	x	x	x	x	x	x	x	x	x	x	x	x
25 mph asphalt	x		x		x		x		x		x		x	
	x	x	x	x	x	x	x	x	x	x	x	x	x	x
55 mph asphalt	x		x		x		x		x		x		x	
	x	x	x	x	x	x	x	x	x	x	x	x	x	x
10 mph gravel	x		x		x		x		x		x		x	
	x	x	x	x	x	x	x	x	x	x	x	x	x	x
15 mph gravel	x		x		x		x		x		x		x	
	x	x	x	x	x	x	x	x	x	x	x	x	x	x

Legend:

cabinet	pump panel
cabin	chassis

This limited chart is in no way all-encompassing. It is provided as a discussion point to underscore the immensity of the task. Of the 156 possible combinations shown in the chart, several data sets must be obtained. In fact, a full evening of collecting pump operation data with the Sterling Fire Department only represents the seven green cells of the matrix. This data can be seen in the two-hundred and seven plots of analog and spectral content of the operation.

Coordinating and planning the full range of recordings in Table 11 across a range of fire departments and differing training schedules would easily require months of planning and effort. It was therefore the intent of this project to:

1. Estimate the range of vibrations induced by engines and pumps
2. Design a sensor and data acquisition system to record vibration data,
3. Validate the system with real world data, and
4. Provide this report as documentation for future research efforts.

Efforts for the estimation can be found in the preceding section and Table 10. The successful design and fabrication of a sensor with a novel attachment method can be found in Sections 3.3.2 Required Equipment and 3.3.3 Equipment Fabrication. The implementation of a LabView data acquisition system can be found in Section 3.3.4 LabView Virtual Instrumentation. Real world validation of the sensor and data acquisition system can be found throughout the remainder of Section 3.3 Experimental Planning.

3.3.2 Required Equipment

The original design proposal for this vibration study involved renting a high-sensitivity, three-axis accelerometer. One such tactical grade accelerometer was the Honeywell HG1930 (refer to Figure 19). Such a high-grade sensor would ensure the ability to measure a large dynamic range of vibrations with adequate bandwidth.

One of the drawbacks of using such an accelerometer is cost. At approximately $3,500.00,[55] purchasing such a component would be unreasonable for the purposes of this project. Renting is therefore the logical choice. However, scheduling rental of this type of sensor in conjunction with fire department operating schedules proved challenging.

Figure 19 Honeywell HG1930 3-axis accelerometer[56]

An additional drawback of this particular device is the means of mounting such that the sensor is vibrationally coupled to the fire apparatus. Any fire department would reasonably assume that their donation of apparatus time would be for non-destructive testing. Without modification, the 0.35 pound[57] HG1930 accelerometer would require socket cap screws for mounting. Furthermore, secure mounting with threaded hardware would inhibit rapid positioning of the sensor during vehicle evolutions.

During the course of the project, it was determined that a low cost micro-electromechanical system (MEMS) style of accelerometer met the recording requirements. Refer to Section 3.3 Experimental Planning. The particular sensor chosen was the Analog Devices ADXL335. The individual device package was a 16-pin LQFN Exposed Pad semiconductor.

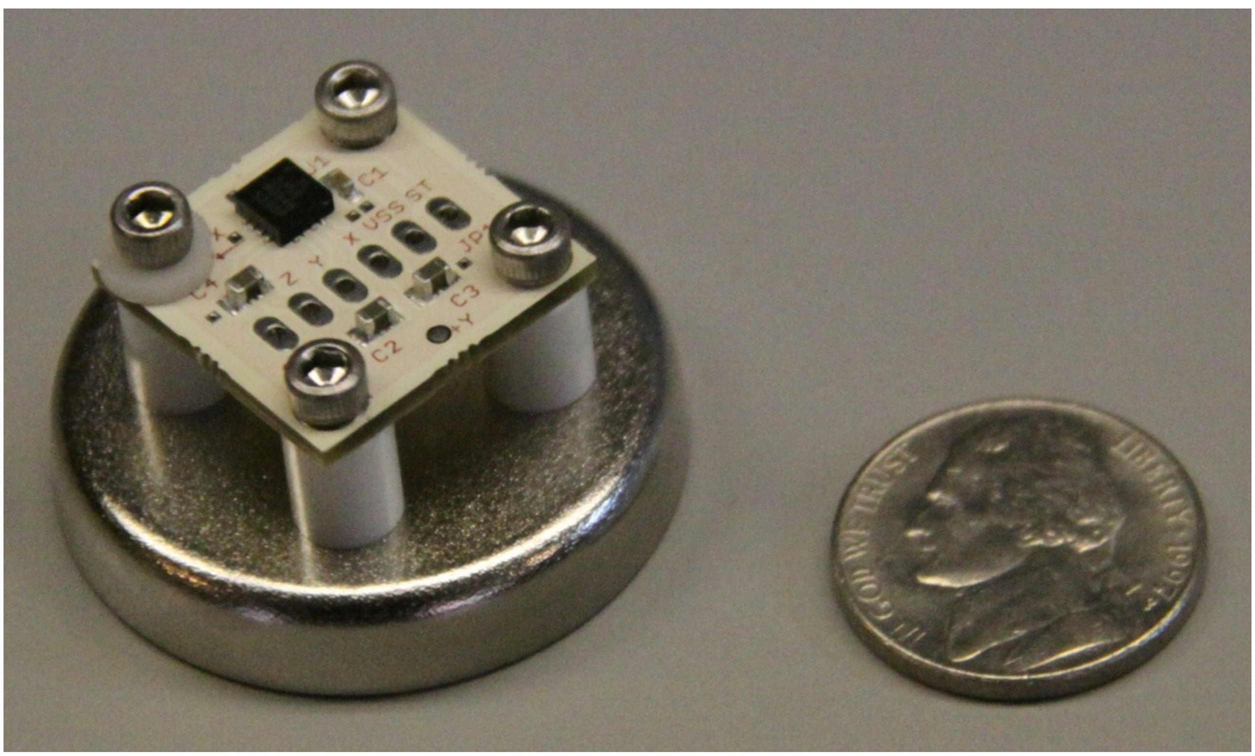


Figure 20 ADXL335 prototyping board and mounting package

At four square millimeters with a height of 1.4mm, the ADXL335 was too small to effectively use in testing (see small black chip in Figure 20). It was feared that in order to effectively connect such a small device to a pumper, it would have to be secured with epoxy or glue for each set of tests. While marginally better than drilling holes in a fire truck, this would have consumed significant amounts of time. Further, there was still a potential of damage to the surface finish of the pumper.

Implementation of this small type of sensor facilitated a novel solution to the mounting issue. A prototyping board that contained the accelerometer as well as the necessary defining capacitors was available from Digi-Key. Securing the board to the truck was implemented using a simple and cheap magnet. Use of a magnet eliminated the need for complicated sensor coupling schemes. Thus the only required accelerometer equipment for the testing was the modified sensor.

Specific instructions for the fabrication of the sensor can be seen in Appendix A: Sensor Fabrication Instructions. Included in these instructions is the parts list for all material needed.

3.3.3 Equipment Fabrication

Fabrication of the sensor was accomplished using the supplied instructions. An advantage of milling a magnet was that it held itself in place throughout the drilling operations. The pattern was partially drilled into the part (equivalent of a center-punch) in order to ensure the pattern was square. This way, if the part broke loose during drilling, the pattern was still square. This step turned out to be unnecessary as the part never moved.

The magnet was centered on the mill using a counter-sink (refer to Figure 21). The countersink was then replaced with a #43 drill bit and the pattern was marked using the dial gauges on the sides of the mill (refer to Figure 22). The holes were then drilled to their full depth as specified in the instructions (refer to Figure 23). Finally the holes were hand-tapped using a 4-40 tap (refer to Figure 24). The sensor was fully assembled as per the instructions. An additional strain relief was added by connecting the category 5 cable to an additional magnet (refer to Figure 25). This ensured that the solder joints were better protected from accidental movement of the cable. This also alleviated concern over cable movement causing vibration pick-up at the sensor. Using the schematic in Figure 31, the other end of the cable was attached to the USB-6212 data acquisition device (refer to Figure 26).

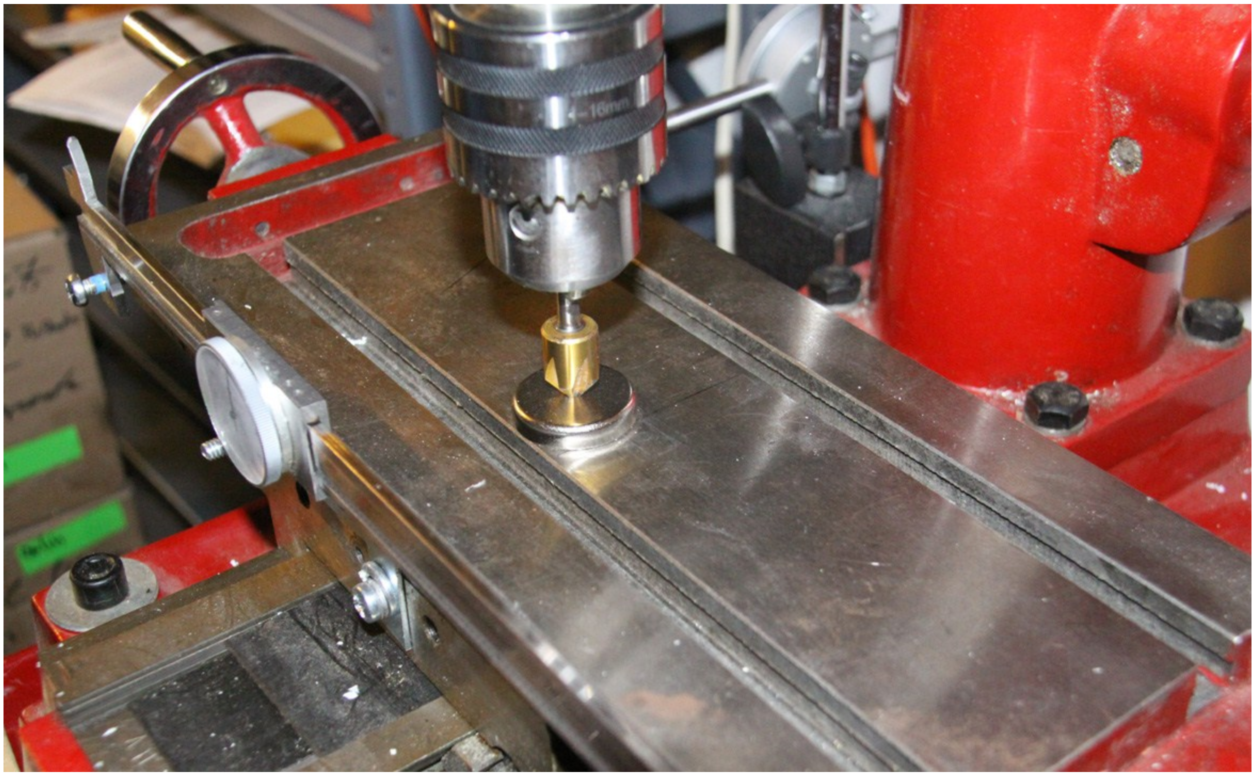


Figure 21 Method for centering the magnet on the mill table

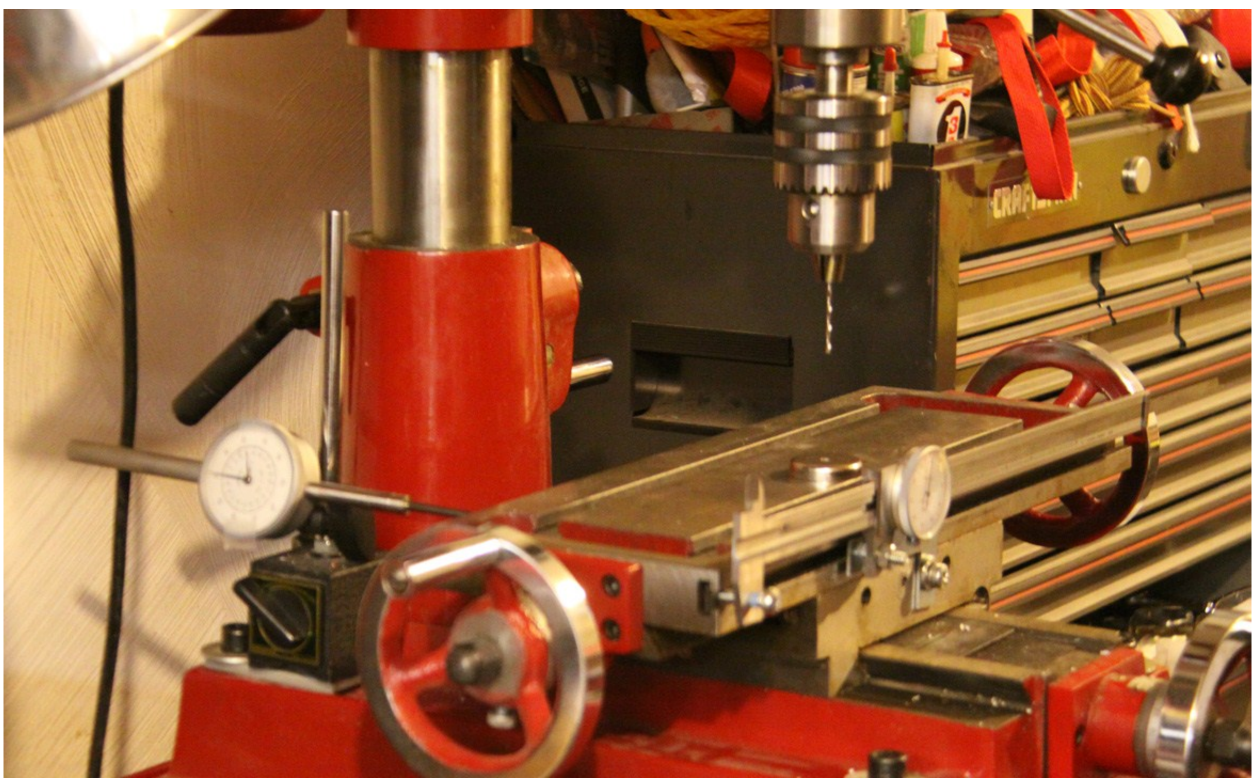


Figure 22 View of mill table showing positioning dial gauges

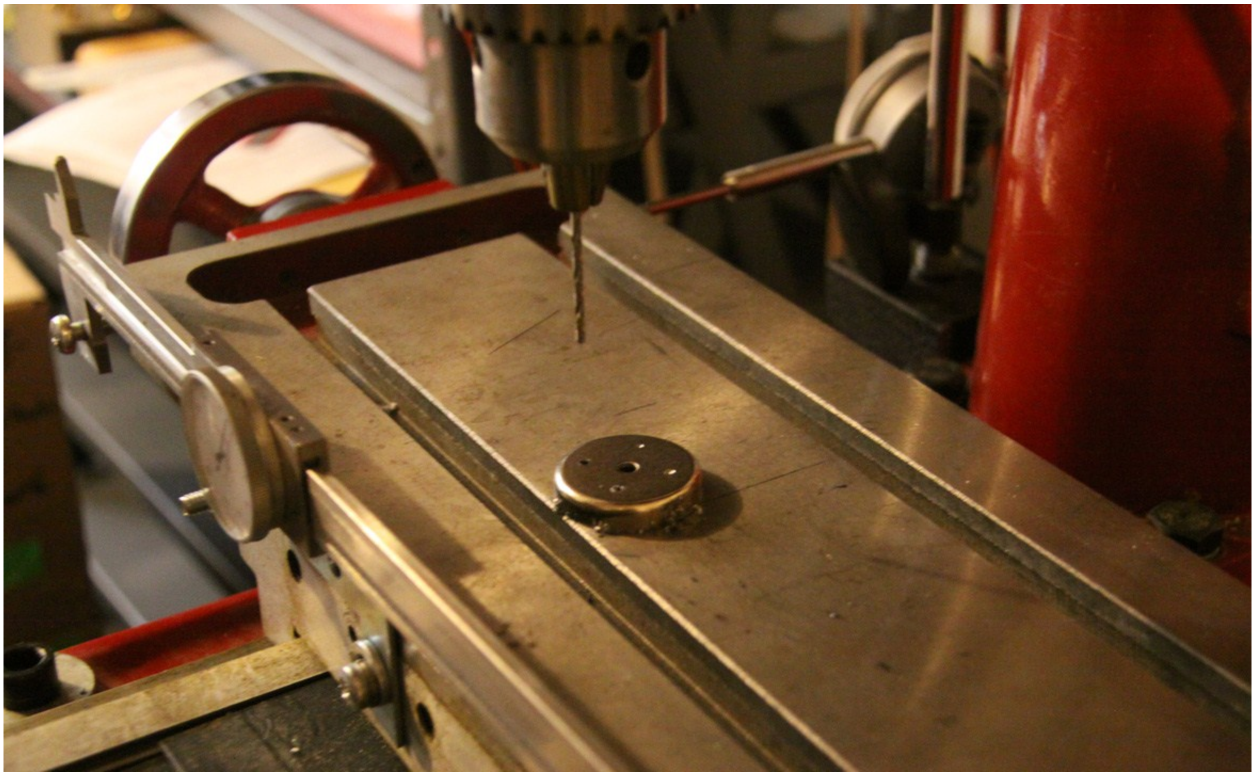


Figure 23 Drilling operation of magnet

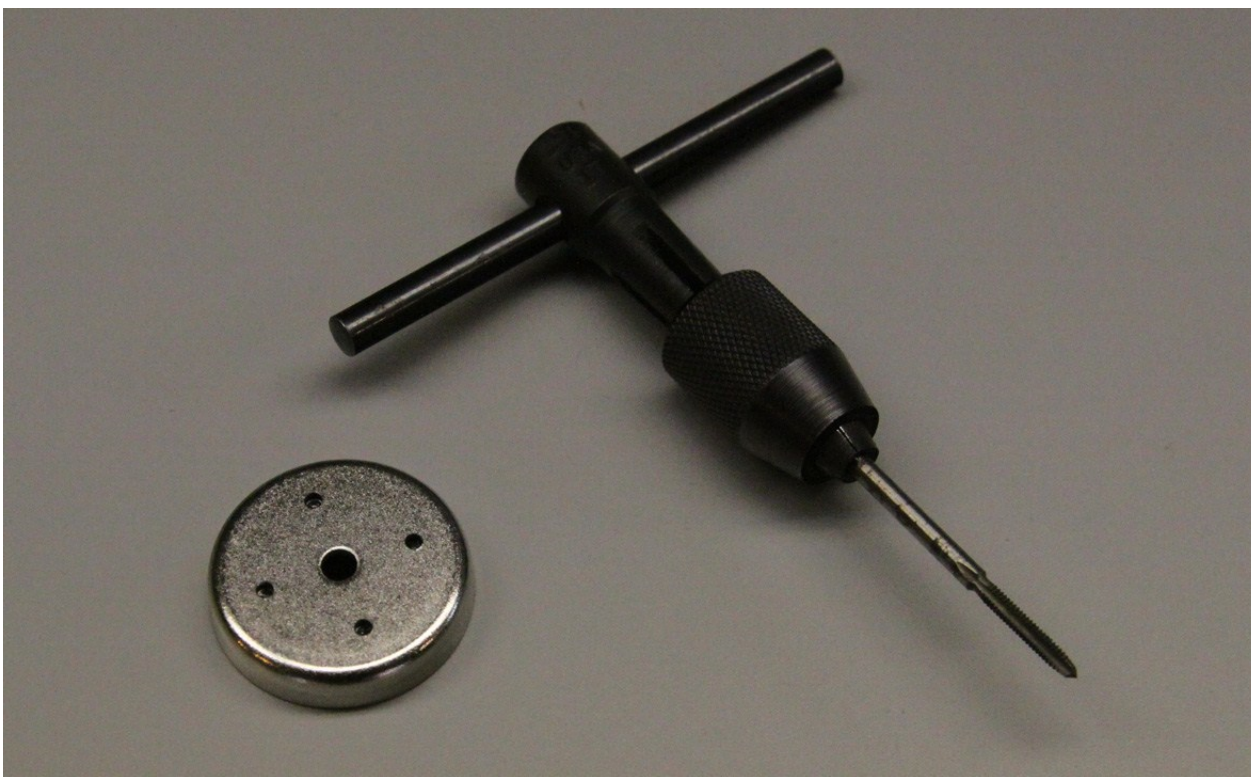


Figure 24 Tap holes prepared for tap

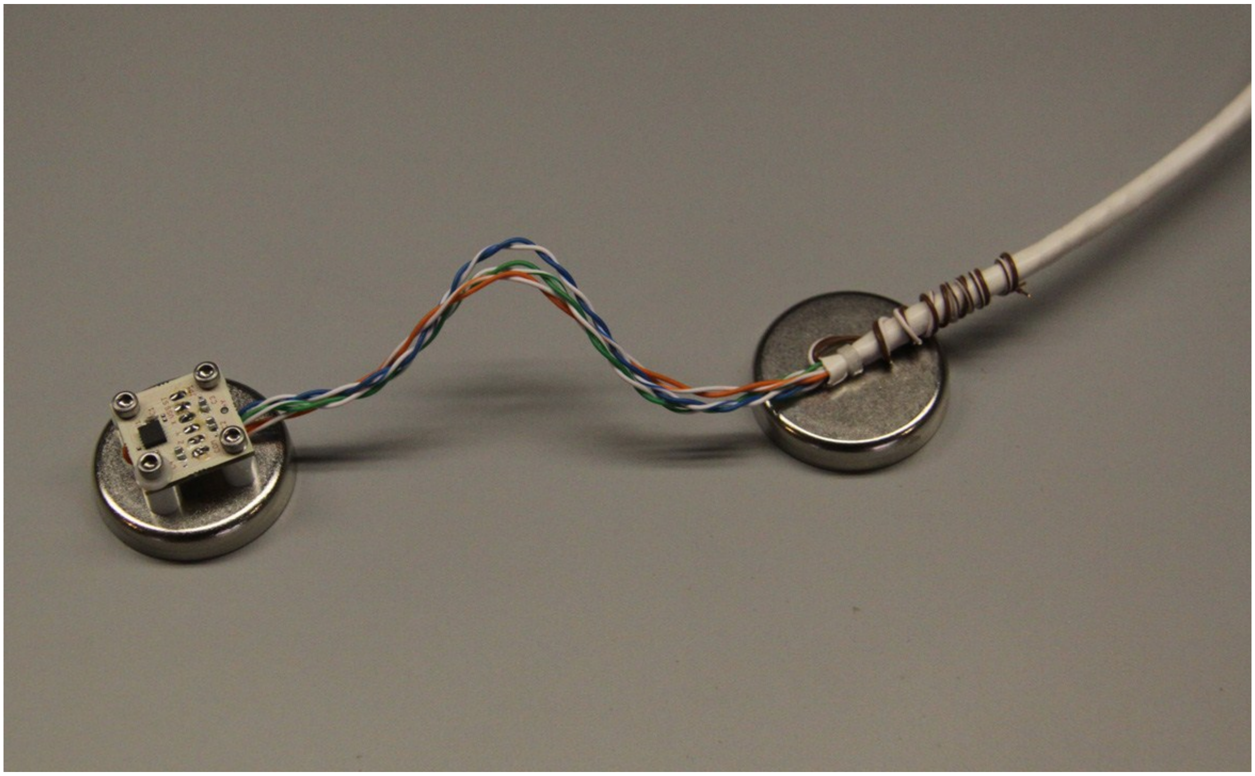


Figure 25 Assembled sensor showing strain relief secondary magnet

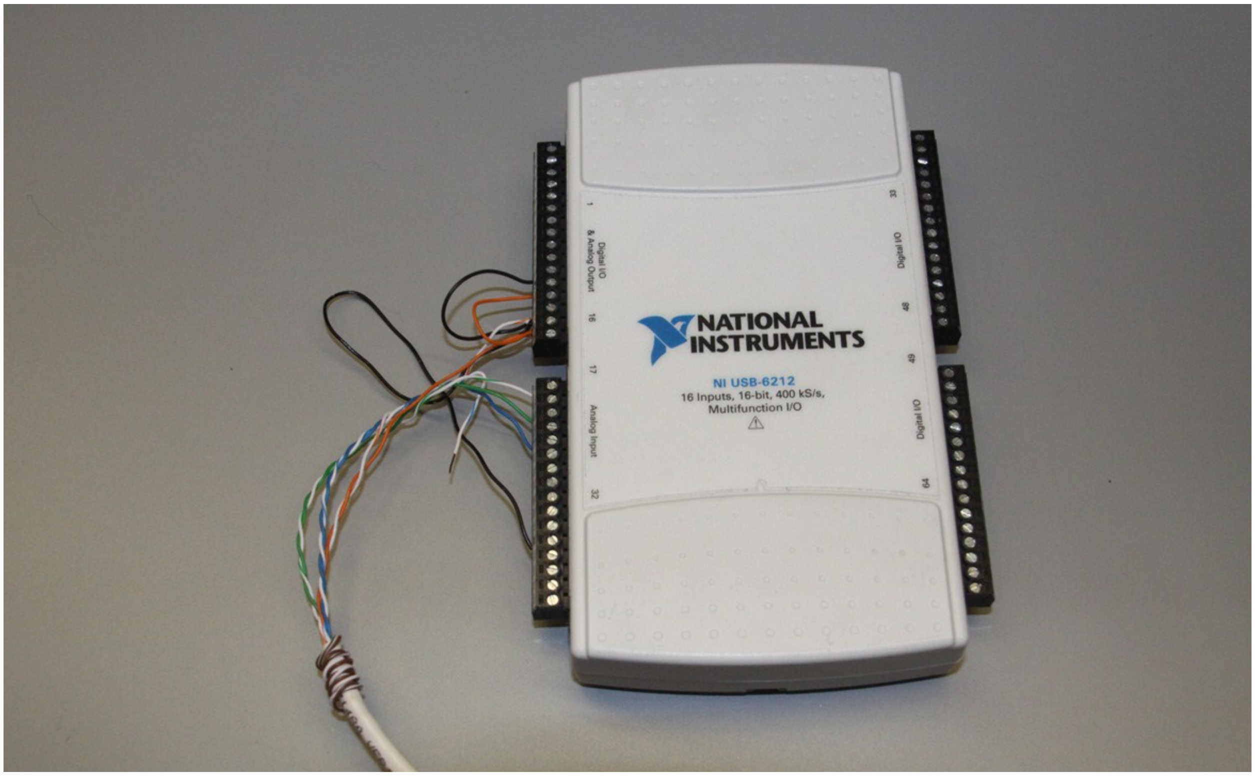


Figure 26 Connection of sensor to USB-6212 data acquisition device

3.3.4 LabView Virtual Instrumentation

Following the fabrication of the sensor, two LabView virtual instruments (VI) were created to (1) record the raw vibration data and (2) to display and analyze the data. For each of the two programs, there is a front panel and a block diagram. The front panel functions as a user interface, allowing operation of the program. The block diagram is used to write the code in a graphical manner standard for LabView. The version used in this project was LabView 10.

3.3.4.1 RecordVib01 VI - Front Panel

The file RecordVib01.VI was designed to measure and record the data from the sensor. For the following description, please refer to Figure 27 which shows the front panel of the VI. In the upper left, a numeric input labeled “Voltage Supply” controls the DC output voltage of the Channel 0 Analog Output. The output voltage is used to power the accelerometer sensor. The ADXL-335 is specified to operate with power supply voltages ranging between 1.8 and 3.6 Volts.

The output of the sensor is ratiometric, meaning a higher power supply voltage will produce a higher output signal. Since the noise level is independent of power supply voltage, the signal-to-noise ratio (SNR) is maximized at the largest possible power supply voltage, or 3.6 volts. There appeared to be no comment in the data sheet indicating what would happen if the 3.6 volts was exceeded other than “damage to the unit.”[58] For the safety of the sensor, it was decided that 3.0 Volts would be the default voltage.

The “STOP” button terminates data recording. Unlike the LabView default stop button, this button stops the while loop (refer to Figure 28), but still allows the data to be written to the chosen file. The default “STOP” button terminates all processes, halting file writing.

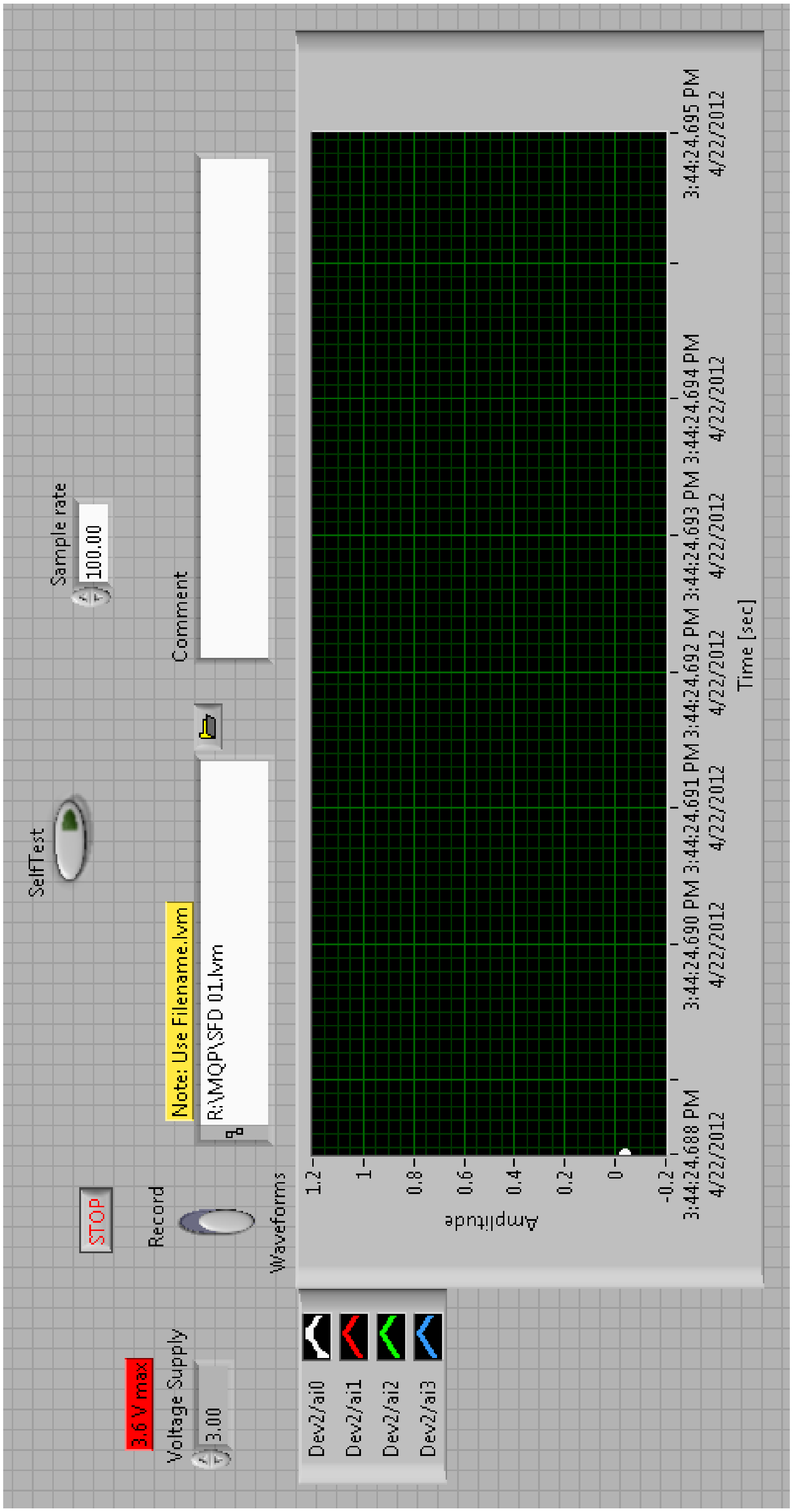


Figure 27 Front Panel of RecordVib01 Virtual Instrument

The “Self Test” button is a momentary push button that generates a digital output voltage (5 volts) when pushed. The data sheet says that the Self Test (ST) pin on the sensor causes an electrostatic force to be applied to all three accelerometer axes when connected to Vs, the power supply voltage. The data sheet cautions “Never expose the ST pin to voltages greater than Vs + 0.3 volts.”[59] Since the self test function was not critical to the project, no signals were connected to this pin. In the future, the digital signal combined with a resistor divider (to reduce the voltage to 3.0 volts) or a second D/A output voltage could be used to drive the ST pin, should the functionality be so desired.

The “Record” button controls whether the vibration data is stored in a file. If the button is down (as in Figure 27), the VI simply displays the data but does not store it.

The “Sample Rate” control determines the conversion rate of the 16-bit A/D converter in the USB-6212 unit. The sensor was factory set by the supplied capacitors to a 50 Hz bandwidth for each of the three channels. This in essence is the Nyquist frequency of the data collection. Thus the sampling rate should be set to twice this number, or 100 Hz, to fully utilize the bandwidth and be consistent with the Nyquist criterion. In the future, the bandwidths of the three axes could be modified by changing the surface mount capacitors on the circuit board. The sensor is capable of a maximum of 1600 Hz for the X and Y axes and 550 Hz for the Z axis.

The “Filename” control determines the name of the recorded file. The format used is the standard LabView text-based measurement file format. The extension for this file is (“.lvm”). Since the data sampling rate is quite low for typical laptop speeds, there is no need to use the higher-speed binary file format (".tdms"). The advantage of the text-based format is that the file is readable by text programs such as Notepad and can be easily imported into Excel.

The "Comment" field allows specific comments to be added during the data collection process.

The Chart display shows the data as it is being collected by the A/D converter. The vertical axis is auto-scaled to keep all the data on the display. The horizontal axis is set up to operate as a strip chart with a maximum of 1024 samples. Once the chart is initially filled with 1024 data points, the display will scroll to the left. New data is added to the right hand side of the chart and the old data is dropped off from the left.

3.3.4.2 RecordVib01 VI - Block Diagram

For the following discussion, please refer to Figure 28 which shows the schematic diagram of the file RecordVib01.VI. For the A/D conversion process, four tasks are established using Analog Input AI0 through AI3. These operate in referenced single ended (RSE) mode. In this mode, the ground potential on the AIGND pin is used as the reference for all four signals. The internal clock of the USB-6212 determines the A/D conversion sample rate, based on the front-panel control.

A "Start Task" block is included to start the A/D process. This, in essence, waits for the actual "Read" commands. Normally only three A/D tasks are required (one for each of the X, Y, and Z accelerometer signals). An additional fourth channel is recorded. The input for this channel could be the power supply voltage of the sensor or any other voltage if desired. If the power supply is monitored, this provides a check to ensure that the D/A converter is working correctly. In this project, the power supply was monitored.

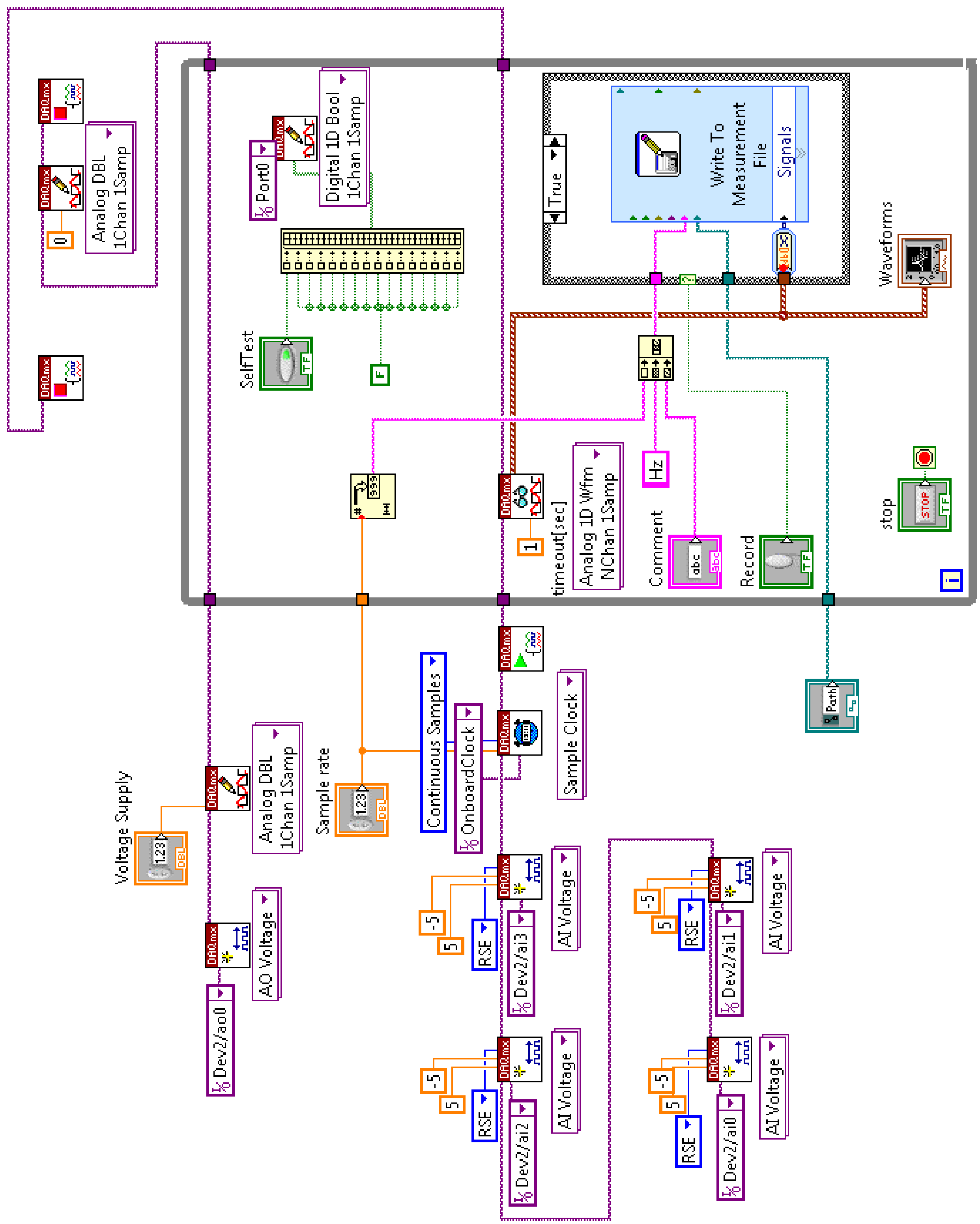


Figure 28 Block Diagram of RecordVib01 Virtual Instrument

In parallel with the A/D, the Channel 0 output at AO0 is set up as an output task. The voltage specified by the front panel “Voltage Supply” control is used to immediately output the voltage to operate the sensor.

The filename is used to generate a Path for the file storage process. This is done outside the While Loop which ensures that changes to the filename will be ignored once the recording process is started.

Inside the While Loop, an A/D conversion is executed with a “Read” block. The digitized data is added to the Waveforms display. In addition, if the “Record” button is in the up position, (Record = True), the write to the file will occur. To keep track of sample rate (without having to write it down), the sample rate number is converted to a text string to which “ Hz” is appended. Additionally, any comment added on the front panel is appended. The full string is then recorded in the file comment field.

Once the process is started, the Record button can be changed at any time. Thus the system could be started but recording could be delayed until an appropriate time. Recording could also be suspended by changing the “Record” button.

As previously mentioned in section 3.3.4.1 RecordVib01 VI - Front Panel, the “STOP” button on the front panel causes the termination of the While Loop. A “Stop Task” block then terminates the recording session and closes the file. In addition, writing “0” to the D/A output causes the AO0 pin to switch from the 3.0 volts to 0.0 volts, ensuring that no voltage is applied to the sensor after the recording session is terminated. The Analog Output task is then terminated with a “Stop Task” block.

3.3.4.3 Playback02 VI - Front Panel

The file Playback02.VI was designed to display and analyze the data recorded from the sensor. For the following description, please refer to Figure 29 which shows the front panel of the virtual instrument.

The “Comment” field displays the comments that were stored in the file, including the A/D conversion sample rate with the appended “ Hz” unit tag.

The “Description” field will display a description if such was added while recording with the RecordVib01.vi program. At present, this function is not implemented.

The “Filename” is the name of the recorded data file.

When reviewing the data, the “SampleRate” control should be set to the conversion rate used in the A/D process. For simplicity of coding, the number must be entered in the current program. In the future, this process could be done automatically.

The “Max Samples” indicator displays the total number of samples for each axis in the file.

The three analog waveforms in the left column show the X, Y, and Z accelerometer signals. Note: the average value for each channel is subtracted for improved spectral displays. This specifically removes the DC bias and avoids any transient due to conventional filtering.

The center three displays show the spectrum of a user-selectable section of the data starting at “Start” and of length “Duration.” The three displays can be used to display the frequency content of a portion of the analog waveform. The “MaxTime” indicator shows the full length of the recorded signal for each axis (derived by dividing “MaxSamples” by the “SampleRate”).

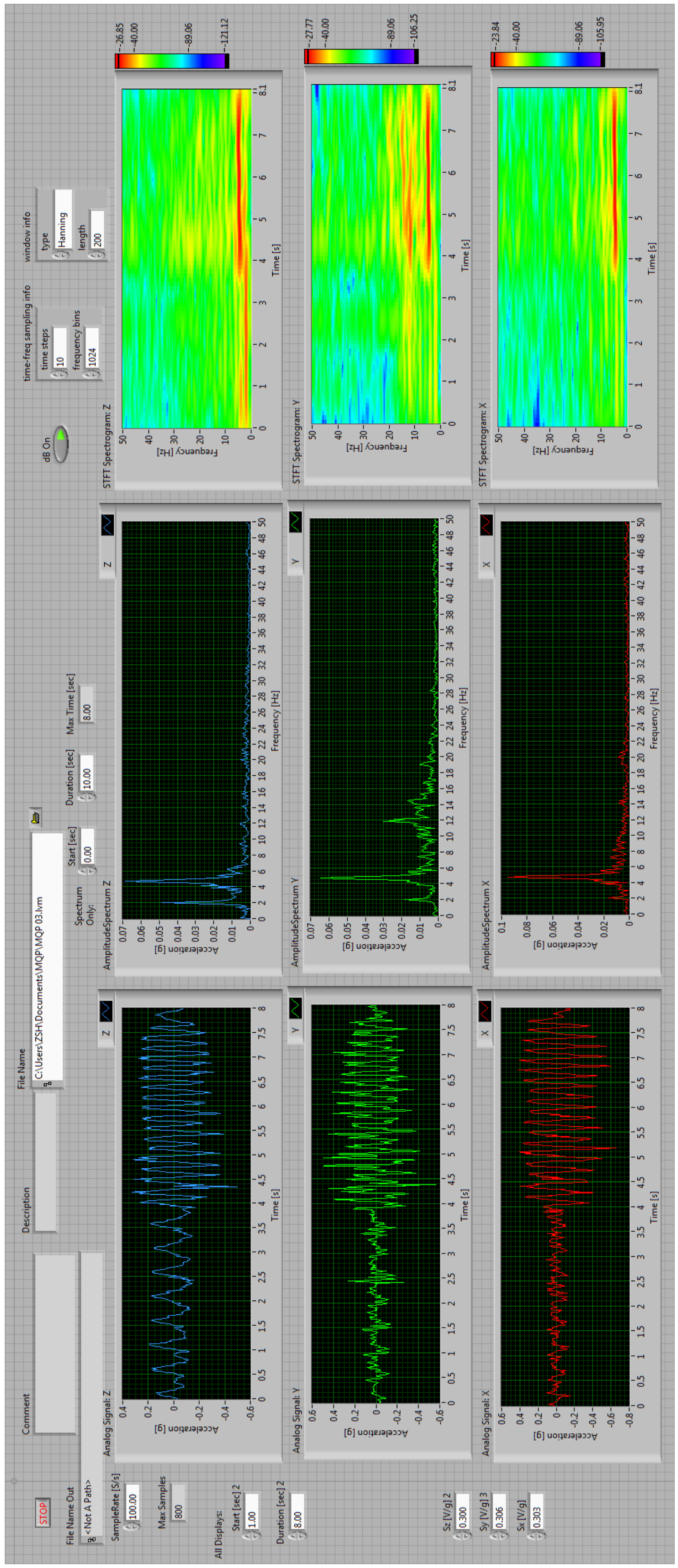


Figure 29 Front Panel of Playback02 Virtual Instrument

The color display at the right is a spectrogram of one of the channels, which is selected by the "Channel" control below the display. The "dB On" control determines if the spectrogram is displayed in decibel units. The spectrogram is controlled by the input controls under the display at the right.

The spectrogram is a plot of a signal's frequency content over time. The plot is generated by the Short Time Fourier Transform (STFT) technique and is fully described in the LabView documentation.[60] Briefly, the STFT involves taking a short time slice of data (for example, 1 second) and converting to frequency using either the discrete Fourier Transform (DFT) or the fast Fourier transform (FFT) process. The result of the transform is then displayed in a vertical column, with the amplitude of the transform converted to an intensity color (note the scale on the right). Another time slice of data is then selected and the process repeated, with the display of the result in a column to the right of the first result. The process is repeated for additional time slices until all of the data has been processed.

A window function is included to reduce the spreading of the spectrum due to the finite sampling process. A Hanning window is used as the default window.

The "length" control specifies the length of the window in samples. If selected value of "length" is less than or equal to zero, the VI sets length to the default value of 64.

The "time steps" control specifies the density to use to sample the signal in the joint time-frequency domain and defines the size of the resulting 2D time-frequency array. When "time steps" is less than or equal to zero, the VI adjusts time steps automatically so that no more than 512 rows exist in STFT Spectrogram {X}. The default value was set to 200.

The “frequency bins” control specifies the FFT size of the STFT. If frequency bins is less than or equal to zero, this VI sets frequency bins to 512. If frequency bins is 1, the VI coerces frequency bins to 2. The default was set as 512.

It should be noted that the values for the spectrogram controls, as shown in Figure 29, were adjusted experimentally to produce the best spectrogram resolution in both frequency and in time.

The intensity scale can be operated in auto-scale mode. Alternatively, the scale can be manually adjusted by first converting to manual mode (by right-clicking the intensity scale at the right and de-selecting auto-scale) and by then double clicking the upper or lower numbers in the scale and entering the desired value.

A final notation should be made regarding colors of the waveform charts, i.e. all but the spectrogram. In both of the front panel displays, the different waveform charts are color-coded using the same color-axis combinations implemented by all major CAD systems. The colors correlate as follows:

- Red : X
- Green : Y
- Blue : Z

3.3.4.4 Playback02 VI - Block Diagram

For the following discussion, please refer to Figure 30 which shows the block diagram of the virtual instrument Playback02.VI.

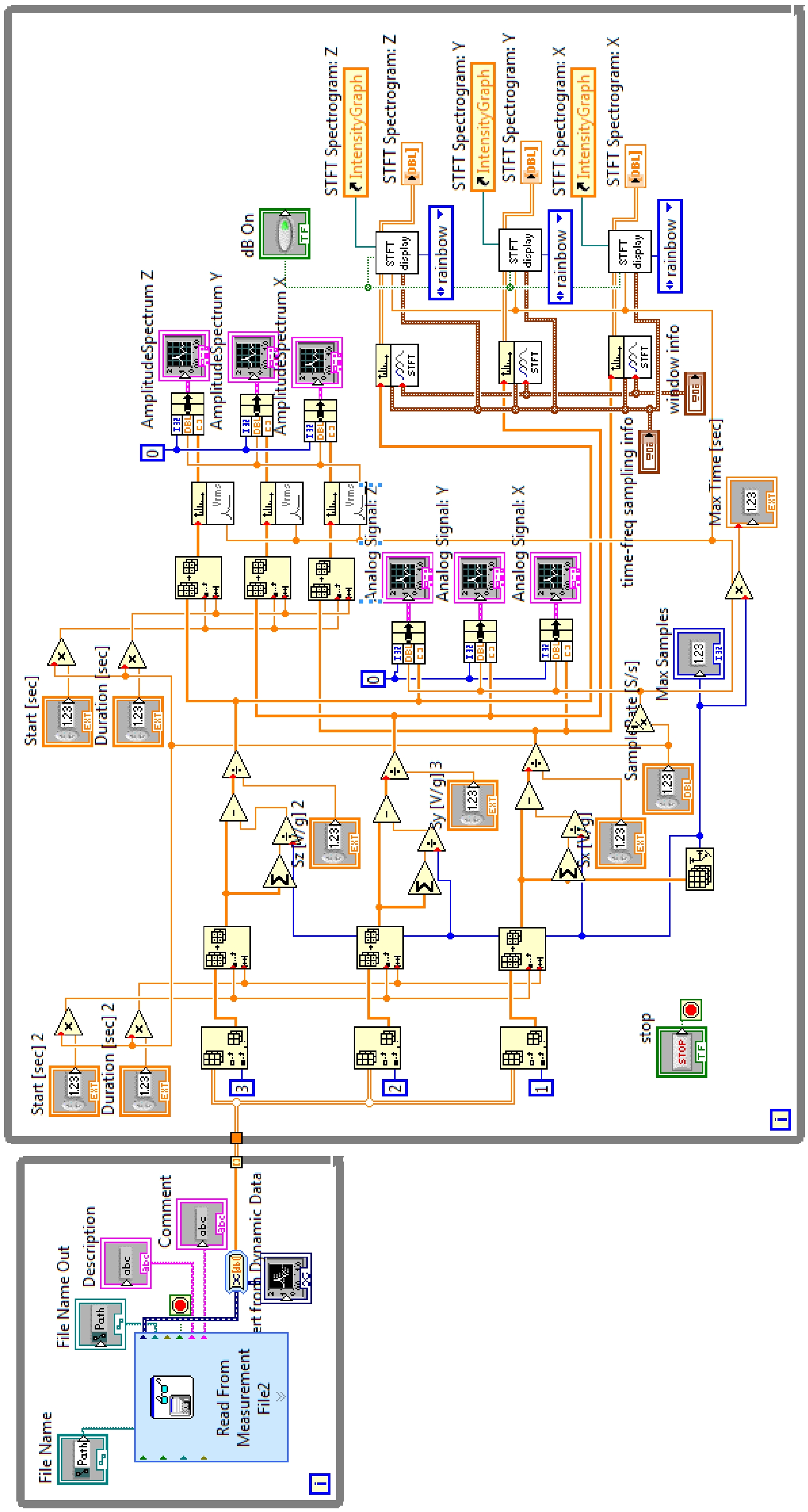


Figure 30 Block Diagram of Playback02 Virtual Instrument

The While Loop on the left executes once and reads the data from the stored file in the laptop. Control is then transferred to the second While Loop, which continues to execute until the "STOP" button on the front panel is pushed.

Three Index Array blocks separate the X, Y, and Z data. The average value of each channel is generated by a summation block in conjunction with a divider that divides the total by the number of samples in the channel. As noted before, this acts to remove the DC bias present on any of the three channels in such a manner that transients are not created.

The three channels (with zero average value) are displayed by the Ch0:X through Ch2:Z controls. The data for each channel is presented to an Array Subset block which selects a portion of the data based on the "Start" and "Duration" controls on the front panel. The outputs of the Array Subset blocks are then converted to a spectral plot using an "amplitude and phase spectrum" VI.

The front panel "Channel" control determines which of the three channels is selected by a Case Structure block. The output of this block is then presented to the STFT VI, which is a programming example in LabView.[61] The result of the STFT is then displayed as a spectrogram by an intensity graph block.

3.3.4.5 Connections

The electrical schematic for connection of the sensor to the USB-6212 screw terminal device can be seen in Figure 31. In the case of this project, the self test functionality was not used. However, if one did not pay attention, the normal output voltage of the P0.0 port would be 5V. As noted in the datasheet, voltages above 3.6V could be detrimental to the accelerometer.

Therefore a voltage divider is provided in the schematic. Using common resistor values, the divider would bring the value of the self test signal to roughly 3V. The resistance values were chosen such that they (1) were small compared to the input impedance of the accelerometer and (2) were large enough to prevent excess current draw in case the power supply voltage was reduced below 3V. This note is written to prevent damage to the device should one try to replicate the test without realizing the constraint placed upon the accelerometer.

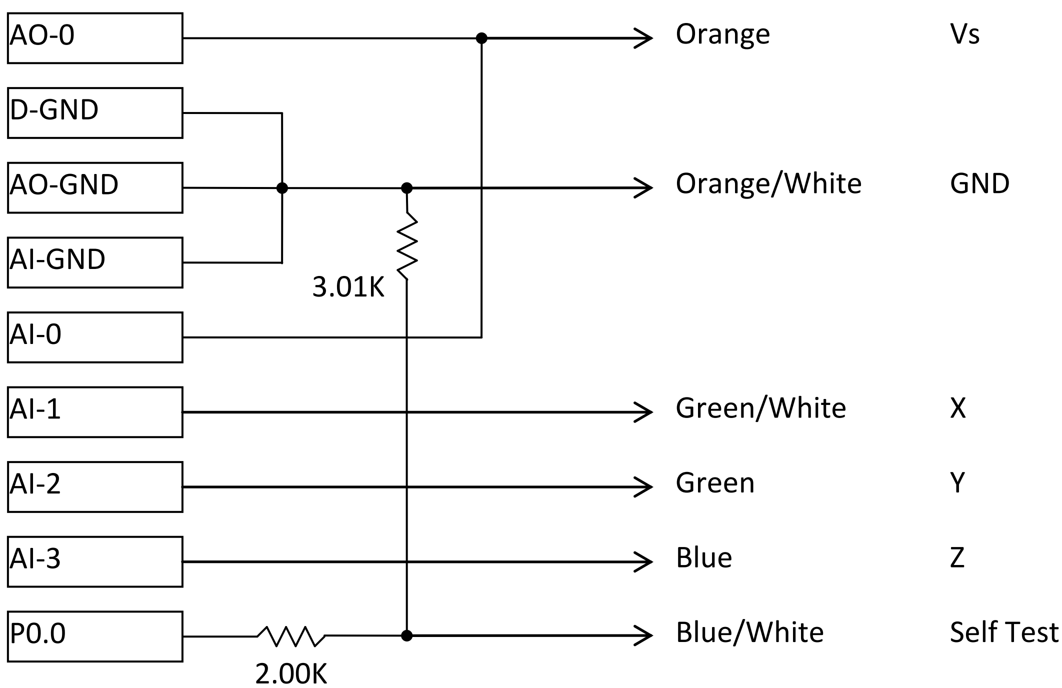


Figure 31 USB-6212 Schematic

Refer to Appendix D: Selected Pages from National Instruments USB-6212 Manual for specifics on the pin-outs of the USB-6212.

3.3.5 Calibration

The ADXL335 accelerometer outputs a voltage. Page 8 of the datasheet (refer to Appendix C: Analog Devices ADXL335 Data Sheet) provided a sensitivity value for each of the three axes in the form of a population chart. The units of the sensitivity are volts per g. The sensitivities chosen were:

$S_x = 0.303$ [V/g]

$S_y = 0.306$ [V/g]

$S_z = 0.300$ [V/g]

These values properly calibrated the charts such that they displayed units of "g" rather than voltage. A quick test was made to verify that the numbers made sense. The sensor was rotated by hand through six orthogonal positions. This subjected the sensor to varying gravity conditions with respect to its orientation. The results can be seen in Figure 32. The graphs showed that the sensor detected +/- 1 g, thus confirming the choice of sensitivity values.

Note that the occasional transient "blips" seen in Figure 32 are due to hand movement while repositioning the sensor.

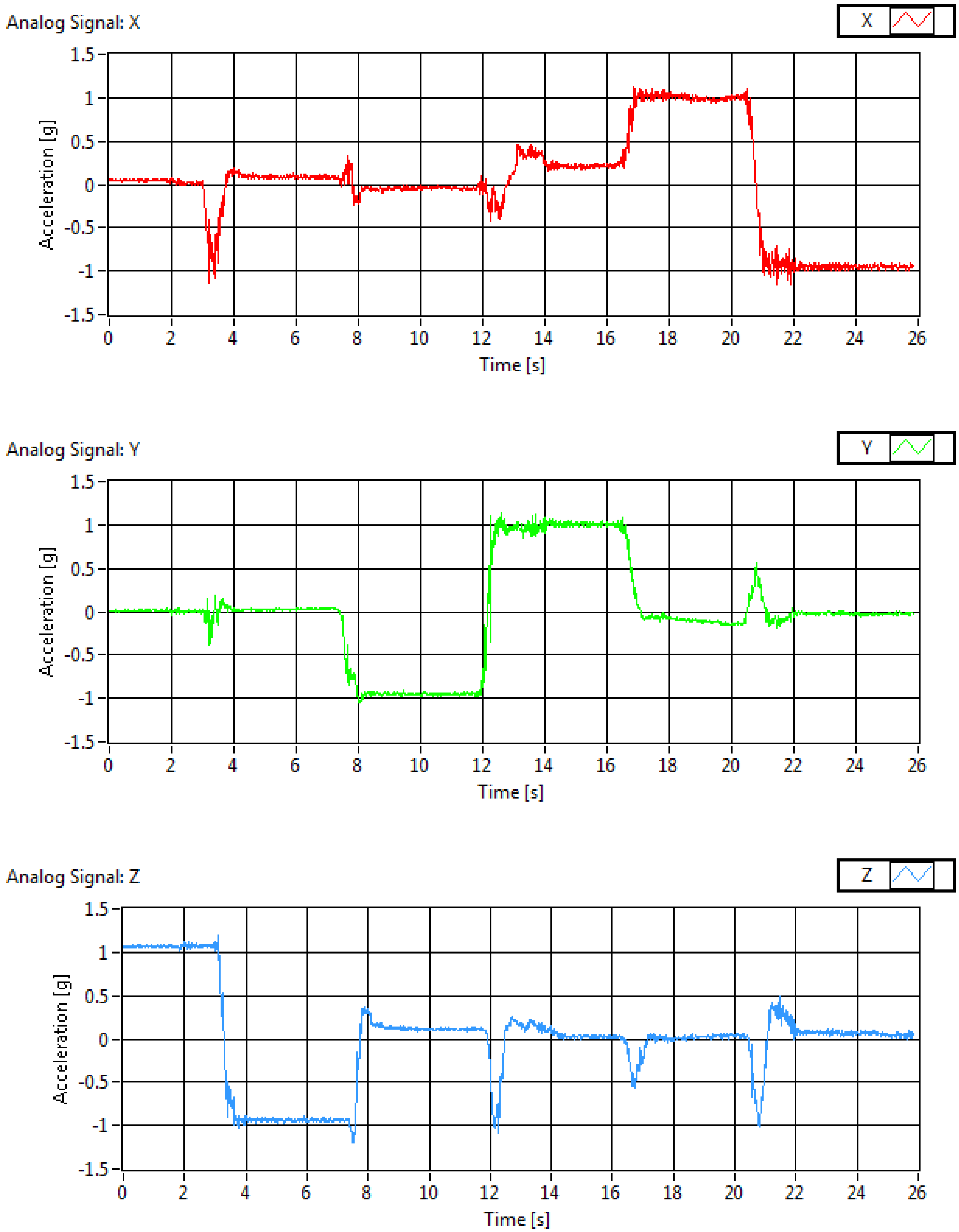


Figure 32 Sensor sensitivity calibration verification

3.3.6 Baseline Noise Characterization

The noise specification of the accelerometer (referenced in Table 12) is provided by its datasheet. Without any further testing, one might assume that the fabricated sensor would perform as advertized. One would, however, be wrong to do so.

Table 12 Noise perfomrance of ADXL335[62]

Noise Density XOUT, YOUT	150	µg/√Hz rms
Noise Density ZOUT	300	µg/√Hz rms

The noise floor of the system must include all possible sources of noise, such as the USB-6212, in order to be meaningful. Rather than calculating the effect of all possible sources, the quickest way was to simply run the sensor in a relaxed state. The sensor was placed on a padded carpet atop a concrete slab. An eight second data record was taken. The analog waveforms of the test can be seen in Figure 33. Using the FFT function of the Playback03 VI, the spectral content of the noise was calculated (refer to Figure 34). A table of noise values follows.

The only noteworthy aspect of the noise is that there appears to be a dominant signal at 40 Hz. It is assumed that this signal is due to the operation of the A/D converter itself. It is possible that this may be a ripple of the power supply from the 5V USB line. This could also be an inherent trait of the converter box such as the input multiplexer switching rate.

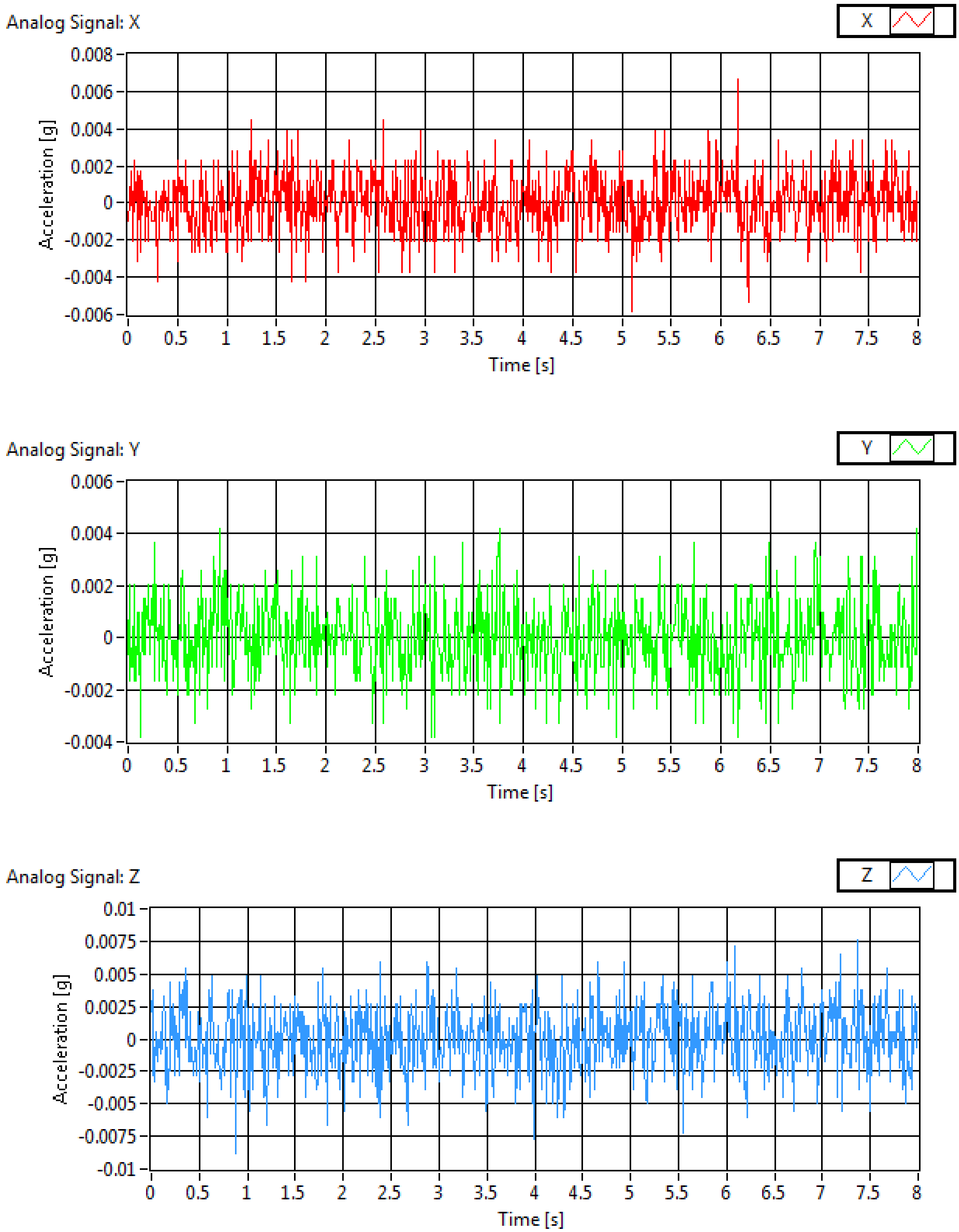


Figure 33 Data acquisition system baseline noise test: analog

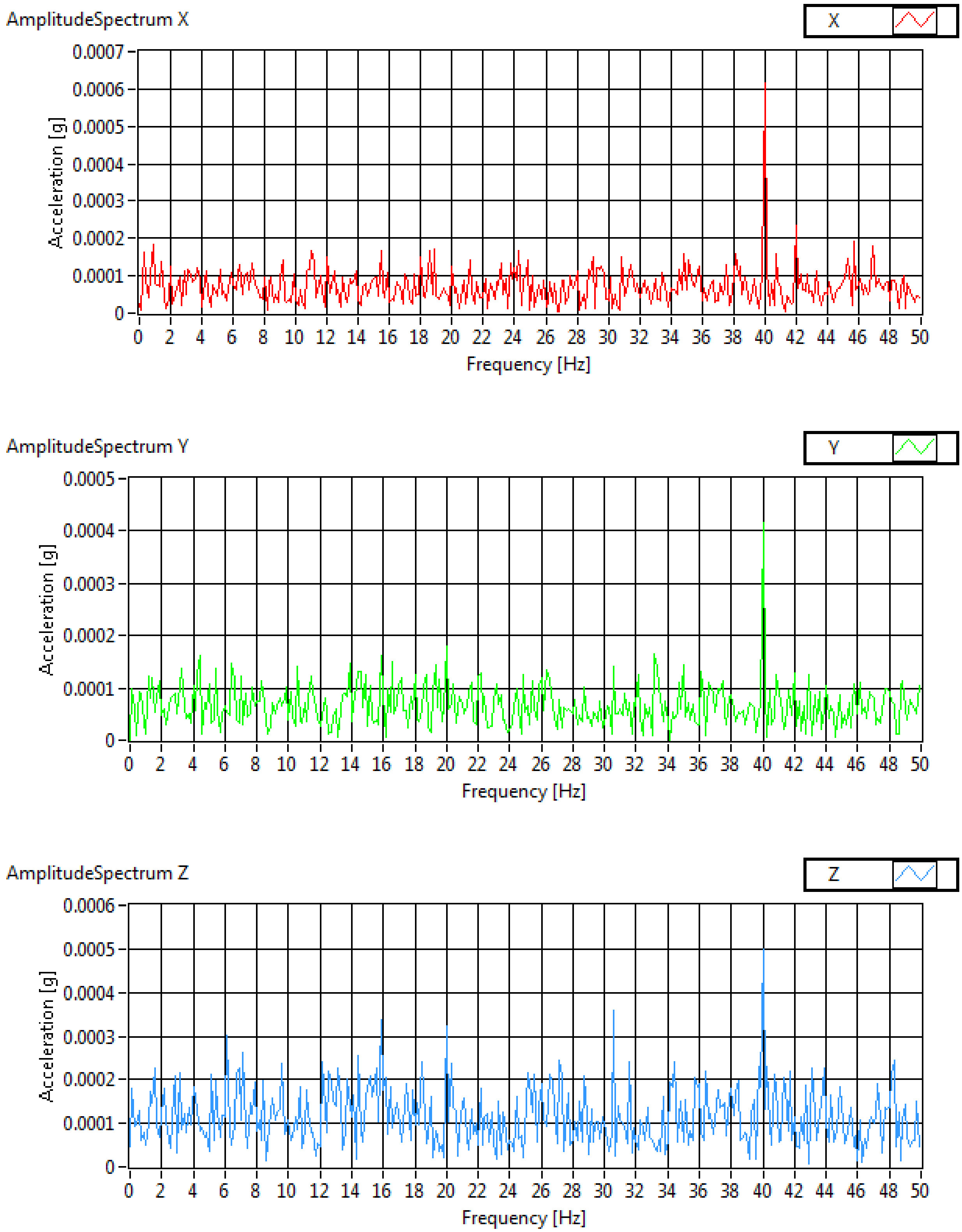


Figure 34 Data acquisition system baseline noise test: spectral

Table 13 Aproximate noise levels of sensor system

	Analog [g]	Spectral [g]	Spectral 40 Hz [g]
X (red)	+/- 0.004	0.00018	0.0006
Y (green)	+/- 0.004	0.00016	0.0004
Z (blue)	+/- 0.006	0.0003	0.0005

The only word of caution to take from this baseline noise characterization is to mind the noise floor of the sensor. In particular, attention must be paid to any 40 Hz spectral content as it runs approximately 1.7 to 3.3 times that of the other frequencies.

3.3.7 Sensor Validation

It was determined that a "sanity check" be performed of the sensor and acquisition system prior to recording with fire apparatus. As the firefighters would graciously be donating their time and diesel fuel, it was only appropriate that the sensor be checked out in advance.

The author's personal vehicle was chosen for this test. Securing the magnet to the aluminum engine block proved somewhat challenging. The sensor was placed inside the engine compartment on the steel top of the wheel well and shock mount.

The car was started, left to idle, and an eight second test was recorded. As there was minimal time variation of the predominant frequency content, it was decided that the spectrograms were unremarkable and were thus not included. The analog and spectral recordings of the test can be seen in Figure 35 and Figure 36 respectively.

The respective recordings ranged from two to five times the amplitude of the observed noise values. While this may not be the world's greatest signal to noise level, it should be noted that fire apparatuses are known to exhibit significantly higher vibrations than that of the engine of an idling coupe. Another way of looking at the conclusion was that measurements of a new and smooth running engine at its lowest rpm were still above the noise floor. Thus the sensor was considered reasonable for the job of recording fire apparatus.

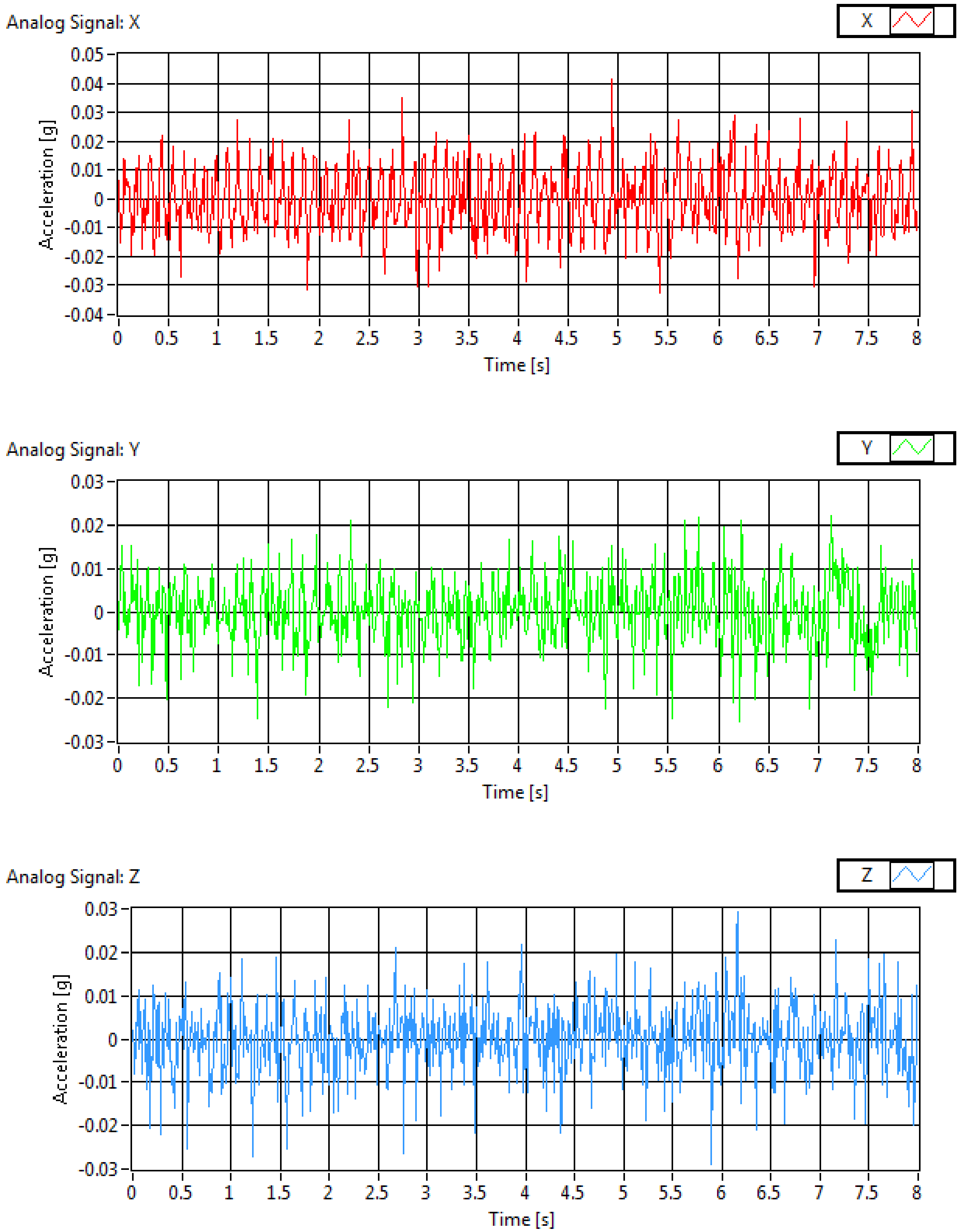


Figure 35 Personal vehicle test: analog

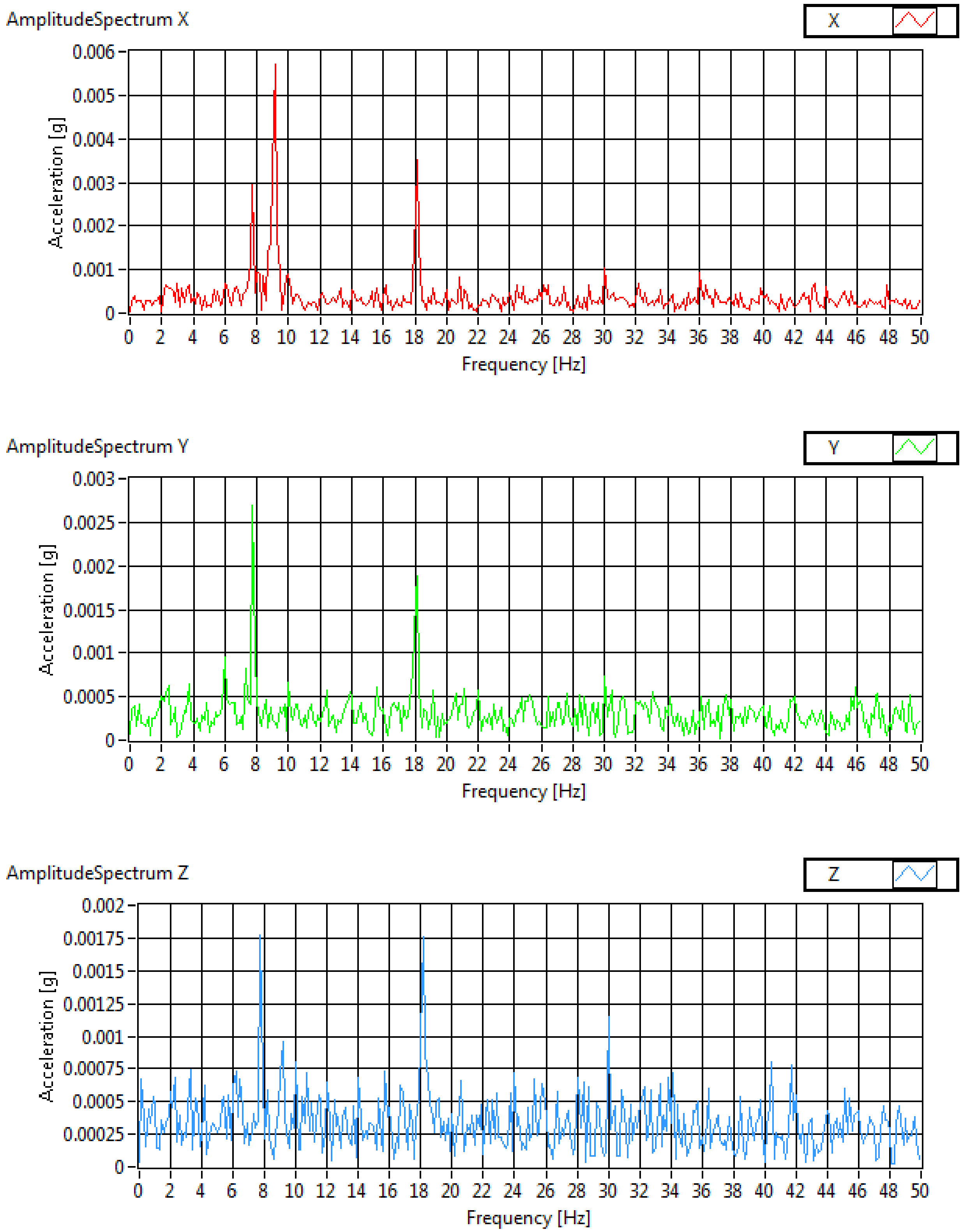


Figure 36 Personal vehicle test: spectral

3.4 Data Collection

Data was collected off of two pumpers during a training exercise with the Sterling Fire Department on 04/18/2012. Data was taken at several different locations. Specifics can be found in the following sections:

3.4.1 Testing Locations and Sensor Positioning

A series of tests was conducted with the Sterling Fire Department on 04/18/2012. The firefighters were undergoing a pump operation class for the evening. Two pumper engines were operated in series from a single hydrant. Engine 4 was connected to the hydrant with a 20 foot length of supply hose (refer to Figure 39). A four inch large diameter hose (LDH) was connected between the two vehicles as shown in Figure 40.

Various exercises were conducted flowing 1-3/4" hand-lines as well as Engine 4's monitor, or deck gun. A range of pumping conditions were present, however, the highest engine speed observed during pumping was 1,100 rpm. Recordings were taken from both pumpers in different locations. A matrix showing the locations of the test samples can be found in Table 14.

Table 14 Matrix of recording test locations

	Driver's-side cabinet over axle (a)	Pump panel (b)	Between pump panel and axle (c)	Jump seat driver's side (d)	Chassis (e)
Engine 4	02,03 01 w/out PTO	04,05,06, 07,08	X	09, 10, 11	X
Engine 2	12,13	X	14,15,16,18,19	20	21

The pump panel location was chosen for Engine 4 as it represented the closest location accessible to the centrifugal pump. This pump was estimated to be the largest contributor to pumping operation vibration as it involved significant mass-flow as well as being coupled directly to the engine. A slightly different location was chosen for Engine 2 as it contained a noisy diesel generator right in front of the rear axle on the officer's side of the apparatus. Refer to Figure 37 and Figure 38 for corresponding "bird's eye" views of the locations referenced in Table 14. Photos of the actual sensor positions can be found in the following sub-sections. Post-processed graphs of the recorded data can be found in Section 3.5 Data Analysis.

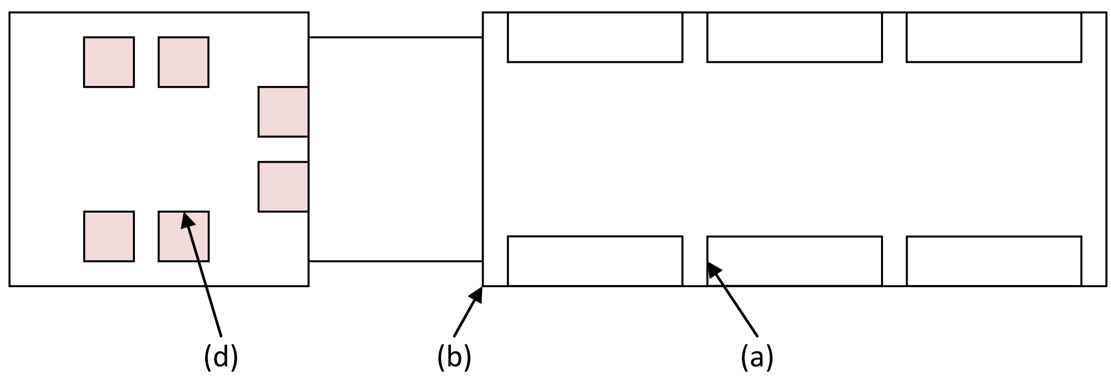


Figure 37 Sensor locations for Sterling FD Engine 4

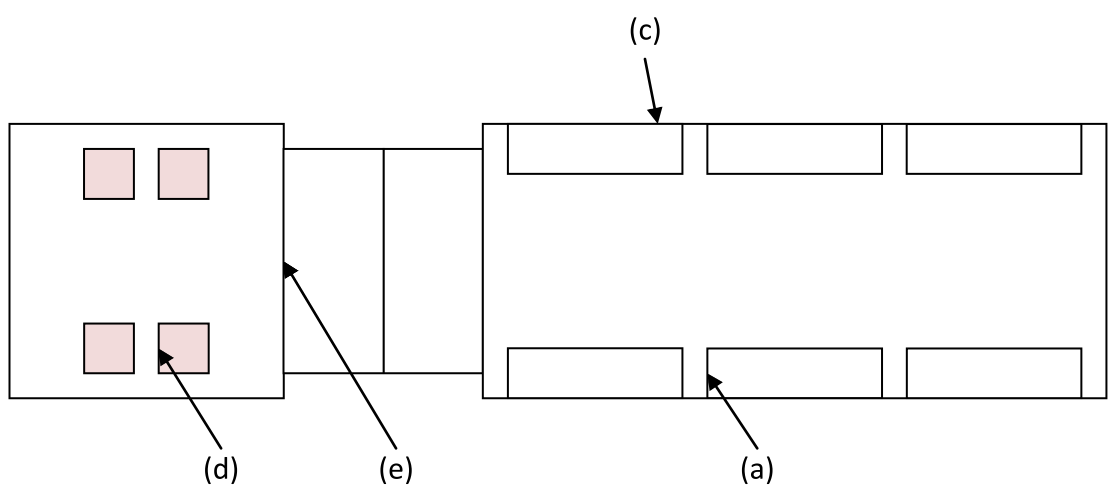


Figure 38 Sensor locations for Sterling FD Engine 2

Figure 39 Engine 4 showing supply hose (white) and LDH connection to Engine 2 (yellow)

Figure 40 Engine 2 (left) and Engine 4 (right) connected by LDH (yellow)

3.4.2 Specific Test Data

The following sub sections describe the test conditions. Figures are presented showing the actual placement of the sensor. Lastly there is a summary table for each of the tests listing the maximum peak-to-peak amplitudes of acceleration.

3.4.2.1 Engine 4 Type (a) Test

The type (a) test of Sterling Engine 4 was conducted in the driver's-side cabinet over the rear axle. Refer to Figure 41 and Figure 42 for the position of the sensor. Three tests were conducted at this location and recorded as tests 01, 02, and 03. The maximum accelerations of these tests can be seen in Table 15. Raw signal graphs of the analog waveform for each test can be seen in Figure 43 through Figure 45.

Test 01 was conducted prior to engaging the PTO to operate the pump. The effect of the engagement of the PTO does not appear significant as it is large in some axes of one test and not in the others.

Table 15 Engine 4 type (a) test maximum accelerations

Test No.	X-axis max [g]	Y-axis max [g]	Z-axis max [g]
01	+ 0.01756 / - 0.01776	+ 0.01894 / - 0.01657	+ 0.04329 / - 0.04507
02	+ 0.01916 / - 0.01888	+ 0.01774 / - 0.02154	+ 0.03340 / - 0.03246
03	+ 0.01402 / - 0.01424	+ 0.01994 / - 0.01988	+ 0.02987 / - 0.03105

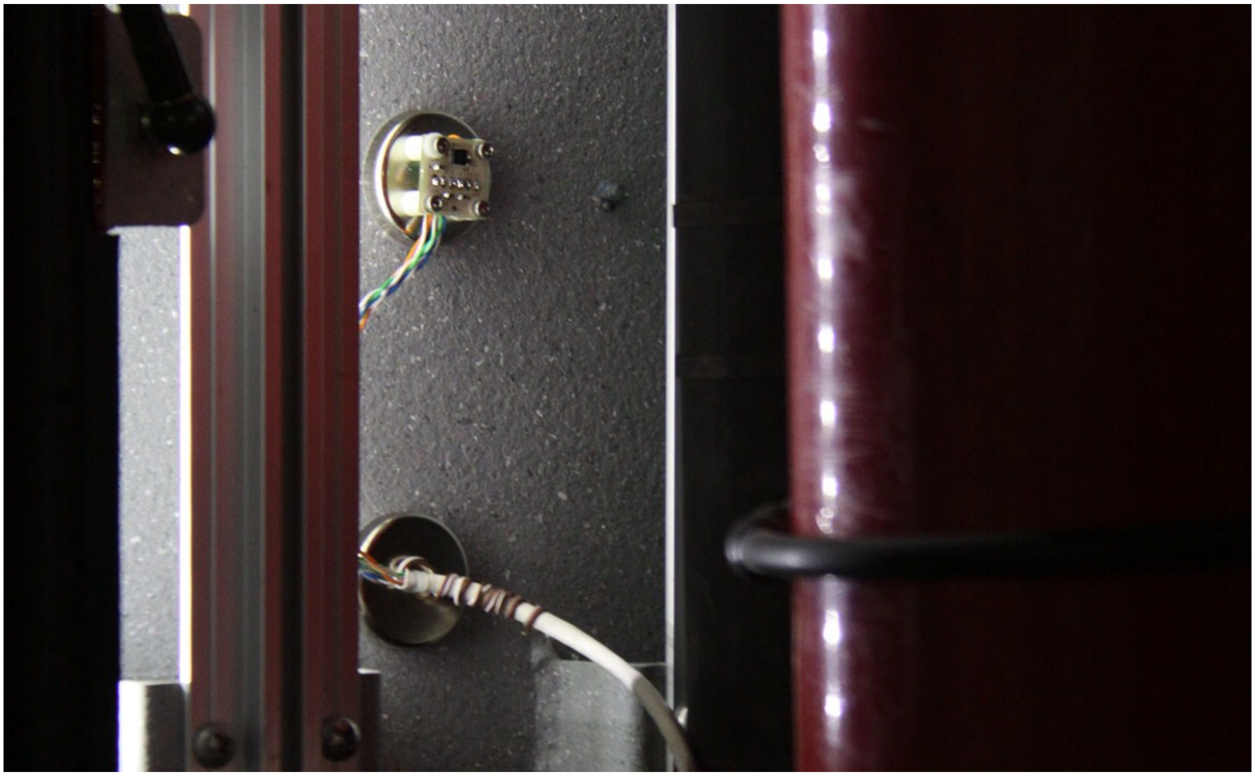


Figure 41 Location of sensor for test (a) of Engine 4

Figure 42 Location of sensor test (a) of Engine 4 (circled) showing computer

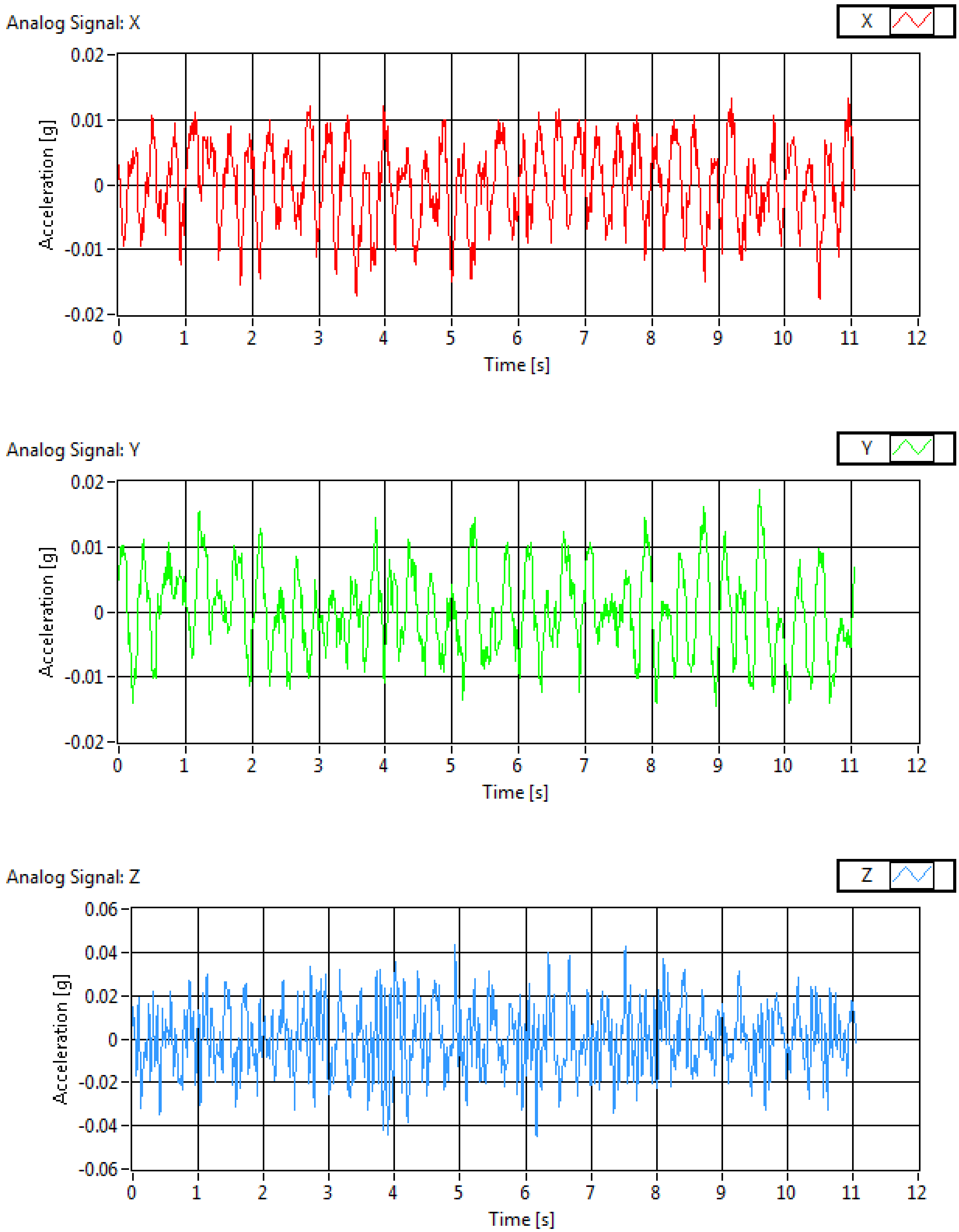


Figure 43 Sterling FD test 01, analog acceleration signals

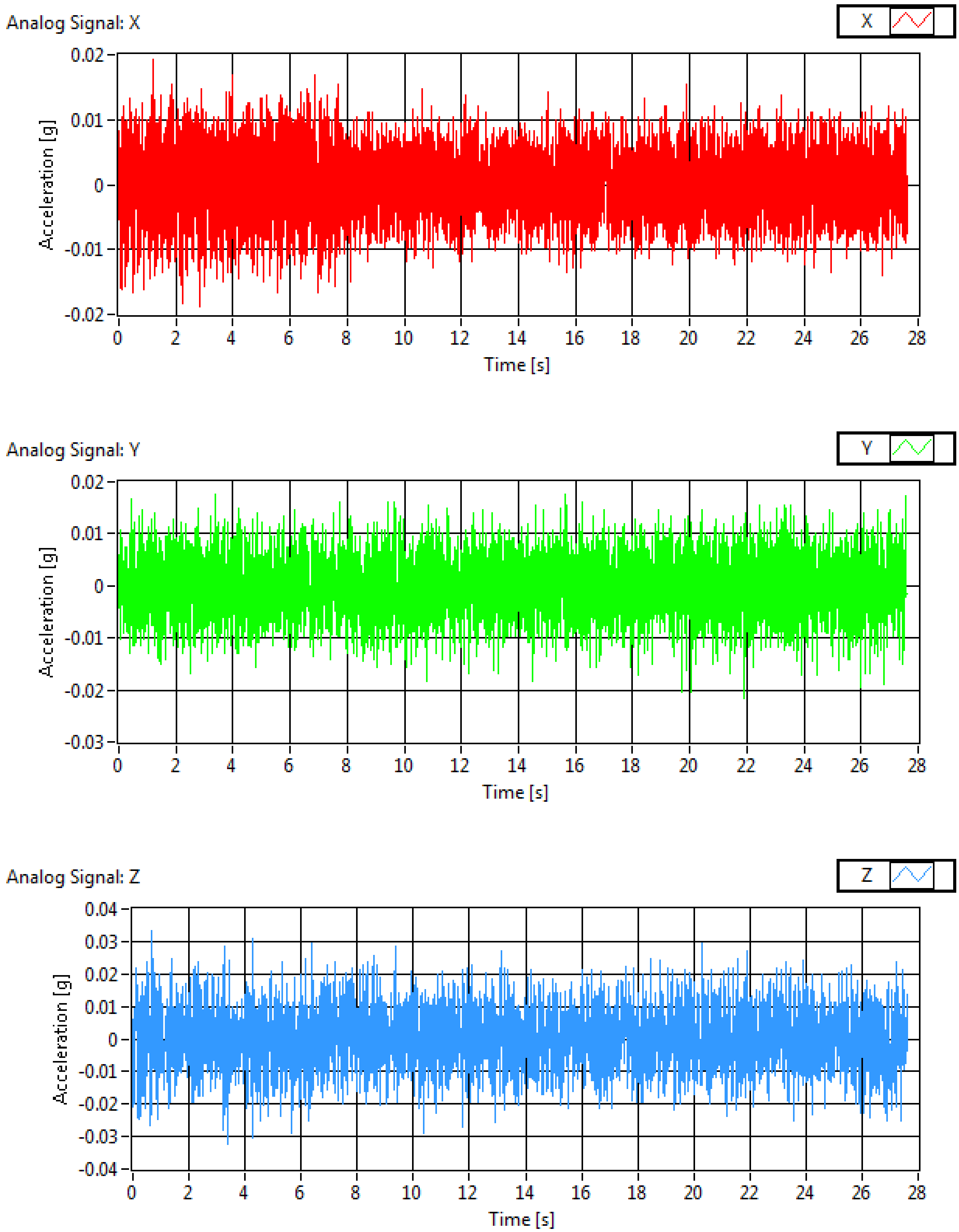


Figure 44 Sterling FD test 02, analog acceleration signals

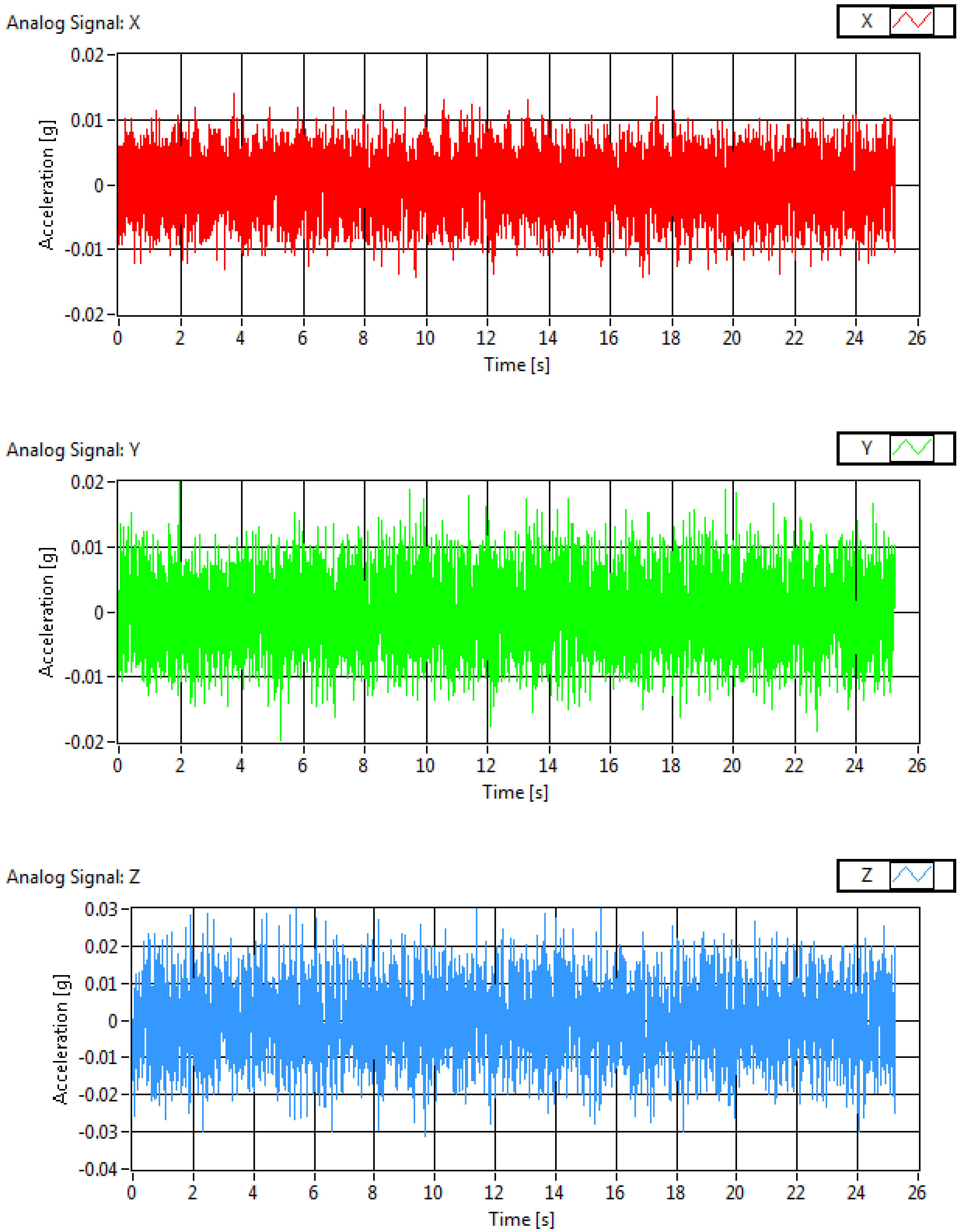


Figure 45 Sterling FD test 03, analog acceleration signals

3.4.2.2 Engine 4 Type (b) Test

The type (b) test of Sterling Engine 4 was conducted at the base of the pump panel. Refer to Figure 46 and Figure 47 for the position of the sensor. Five tests were conducted at this location and recorded as tests 04, 05, 06, 07, and 08. The maximum accelerations of these tests can be seen in Table 16. Raw signal graphs of the analog waveform for each test can be seen in Figure 48 through Figure 52.

Table 16 Engine 4 type (b) test maximum accelerations

Test No.	X-axis max [g]	Y-axis max [g]	Z-axis max [g]
04	+ 0.14370 / - 0.13833	+ 0.16326 / - 0.18219	+ 0.19675 / - 0.19238
05	+ 0.15313 / - 0.16096	+ 0.17881 / - 0.20915	+ 0.23790 / - 0.24069
06	+ 0.07705 / - 0.06206	+ 0.04406 / - 0.05118	+ 0.13345 / - 0.10695
07	+ 0.18210 / - 0.16677	+ 0.15395 / - 0.20550	+ 0.24773 / - 0.26324
08	+ 0.07066 / - 0.08475	+ 0.05315 / - 0.06038	+ 0.11651 / - 0.12608

Figure 46 Location of sensor for test (b) of Engine 4

Figure 47 Location of sensor for test (b) of Engine 4 (circled)

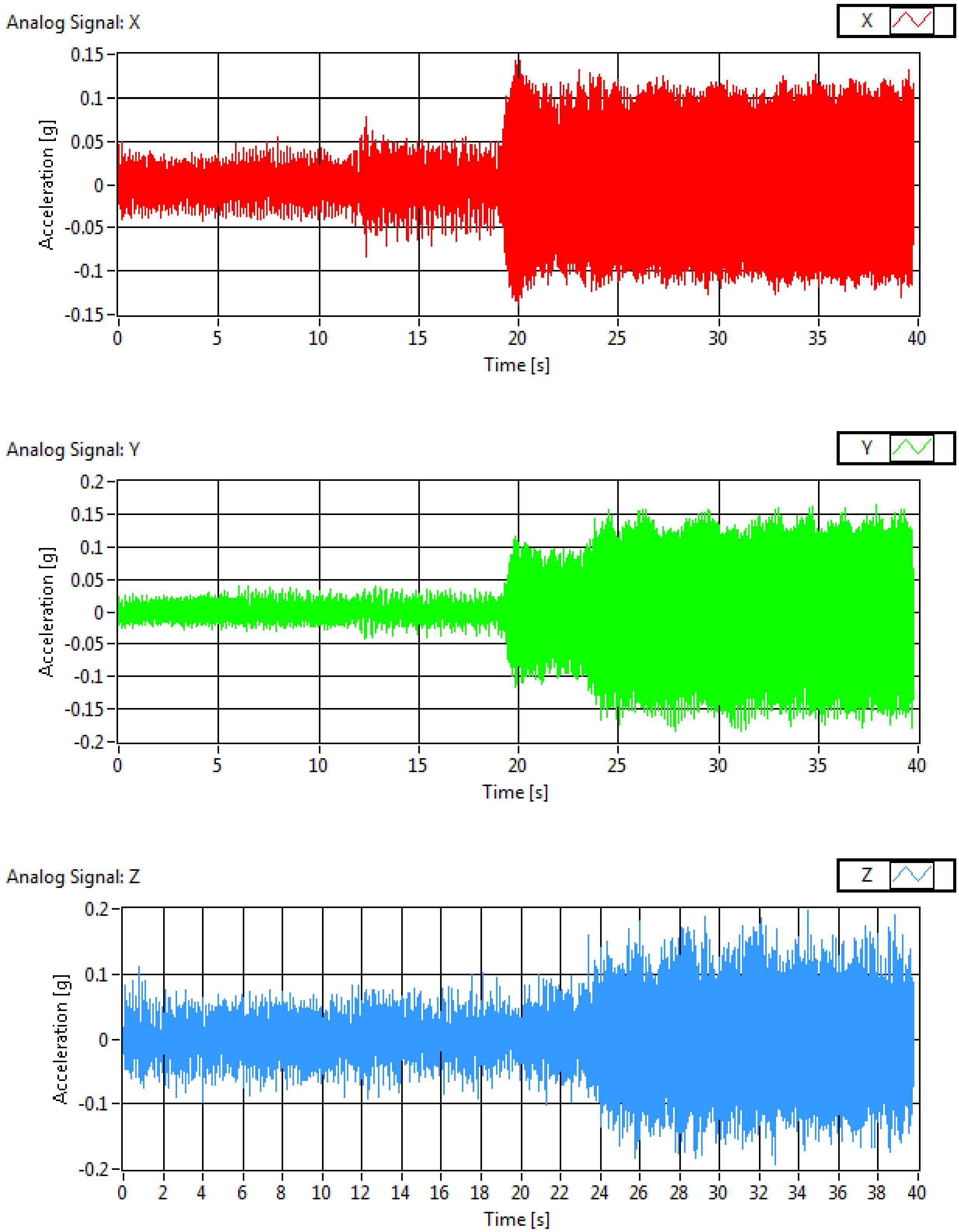


Figure 48 Sterling FD test 04, analog acceleration signals

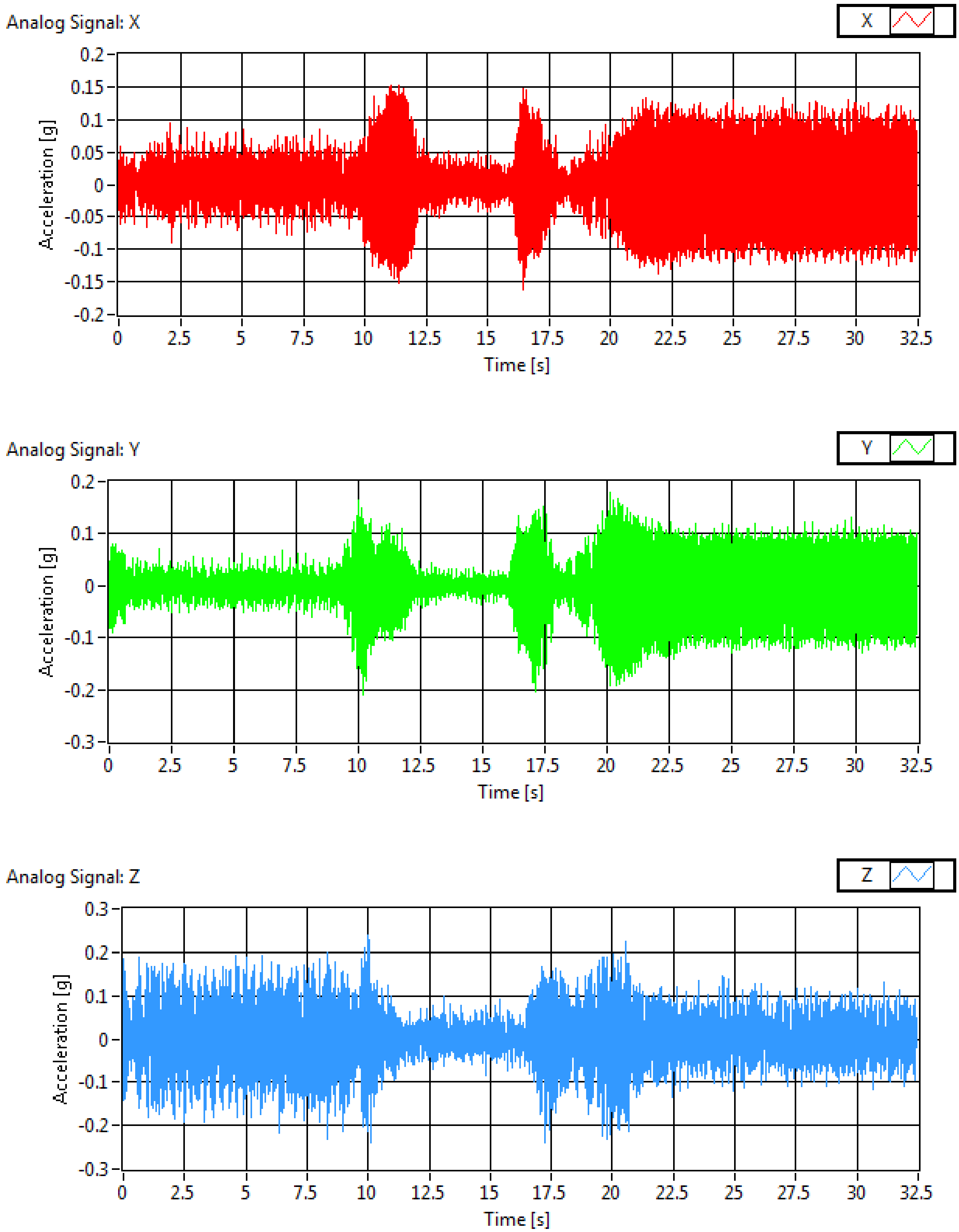


Figure 49 Sterling FD test 05, analog acceleration signals

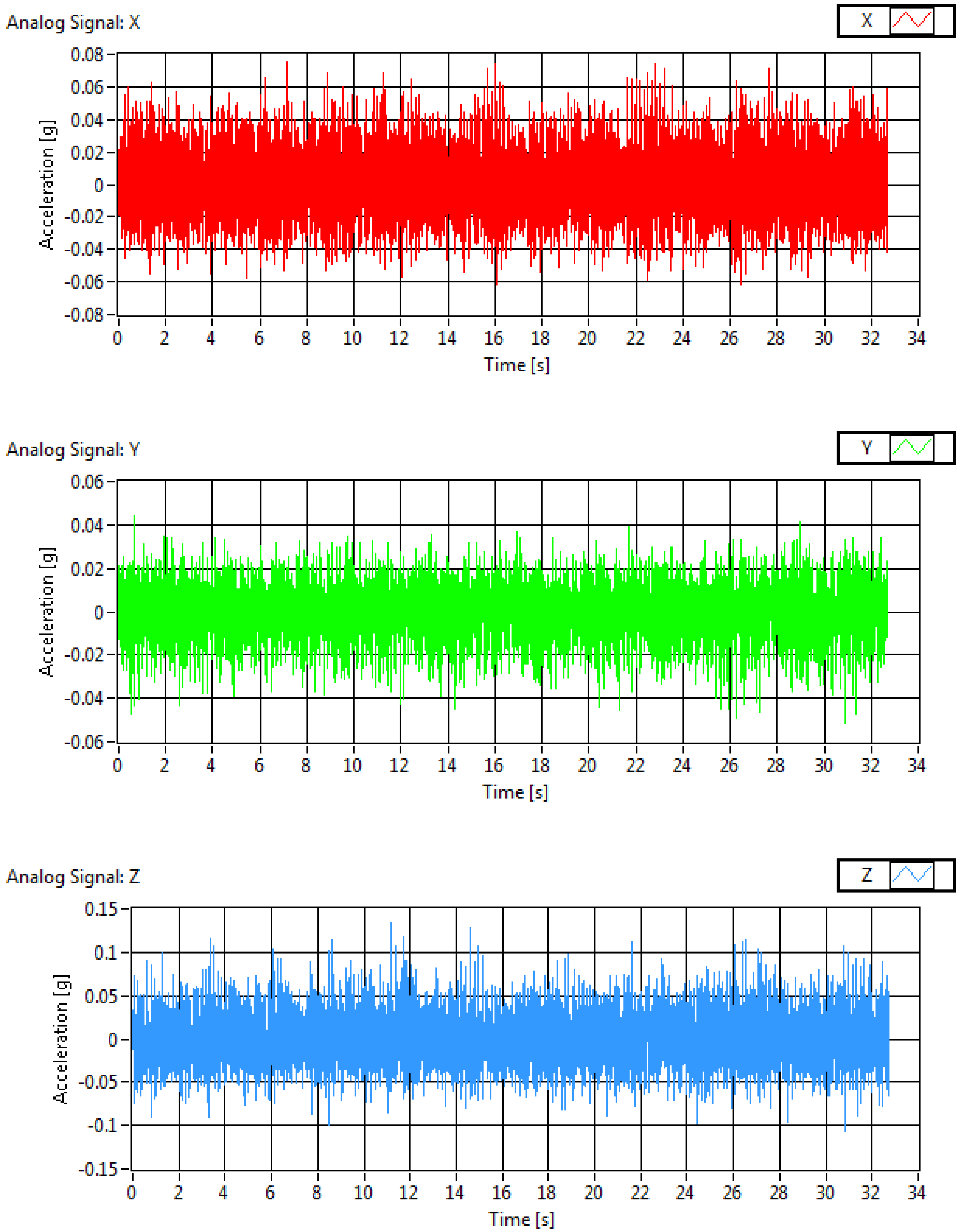


Figure 50 Sterling FD test 06, analog acceleration signals

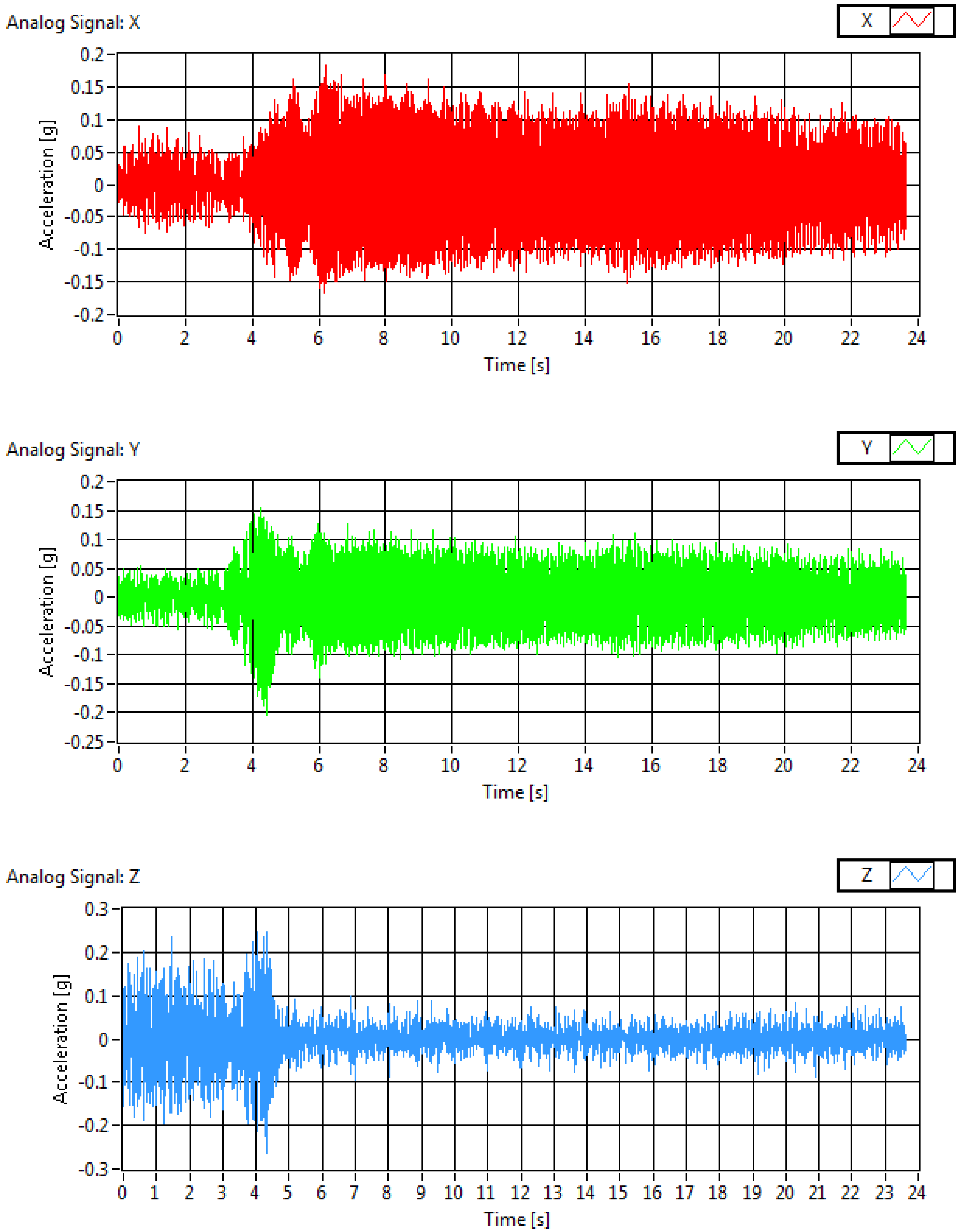


Figure 51 Sterling FD test 07, analog acceleration signals

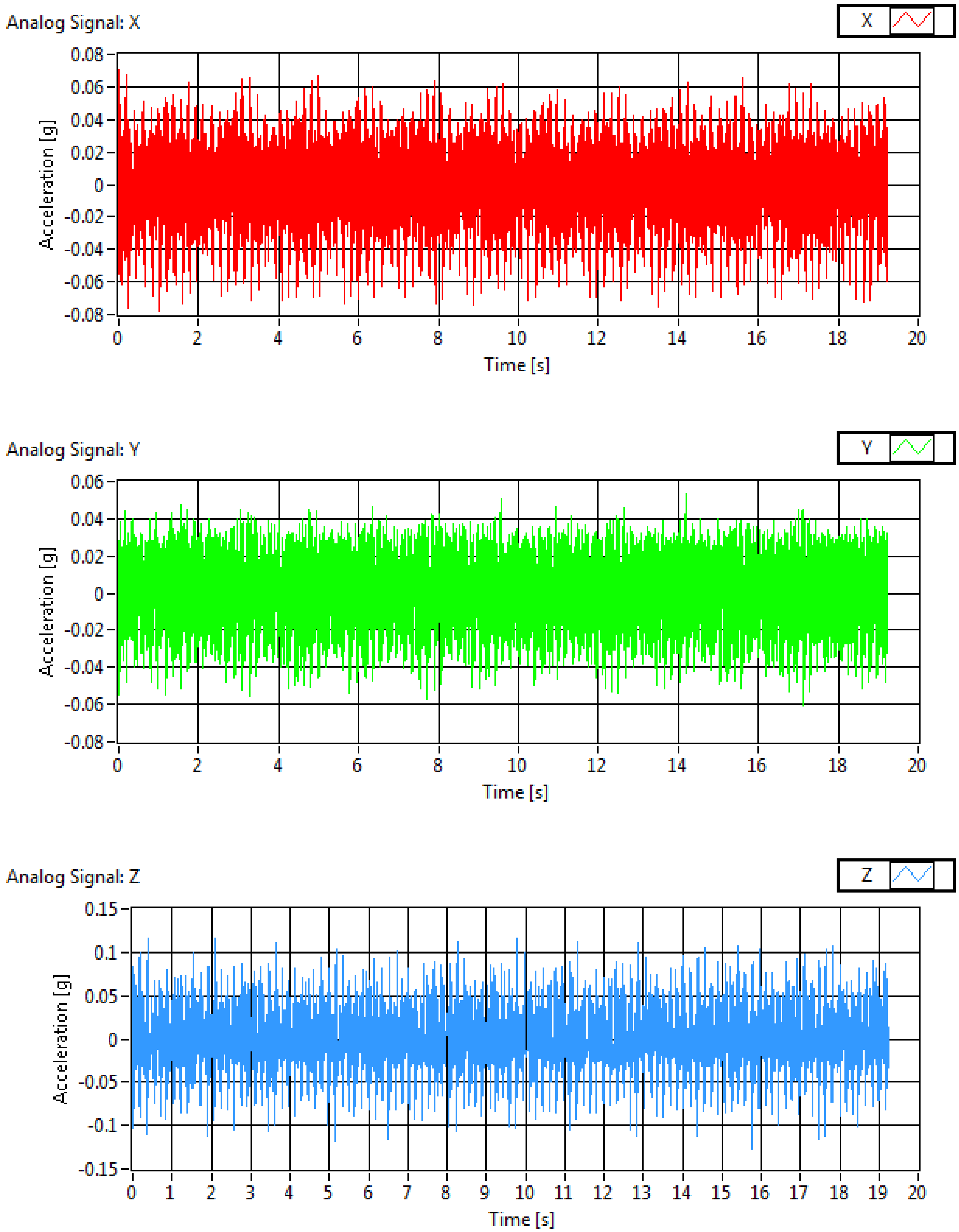


Figure 52 Sterling FD test 08, analog acceleration signals

3.4.2.3 Engine 4 Type (d) Test

The type (d) test of Sterling Engine 4 was conducted on the SCBA frame of the rear driver's side jump seat. Refer to Figure 53 for the position of the sensor. Three tests were conducted at this location and recorded as tests 09, 10, and 11. The maximum accelerations of these tests can be seen in Table 17. Raw signal graphs of the analog waveform for each test can be seen in Figure 54 through Figure 56.

Table 17 Engine 4 type (d) test maximum accelerations

Test No.	X-axis max [g]	Y-axis max [g]	Z-axis max [g]
09	+ 0.03759 / - 0.04881	+ 0.02548 / - 0.02833	+ 0.03635 / - 0.03280
10	+ 0.04168 / - 0.04037	+ 0.03186 / - 0.03056	+ 0.04376 / - 0.04570
11	+ 0.03481 / - 0.03095	+ 0.03389 / - 0.03606	+ 0.04096 / - 0.04082

Figure 53 Location of sensor for test (d) of Engine 4

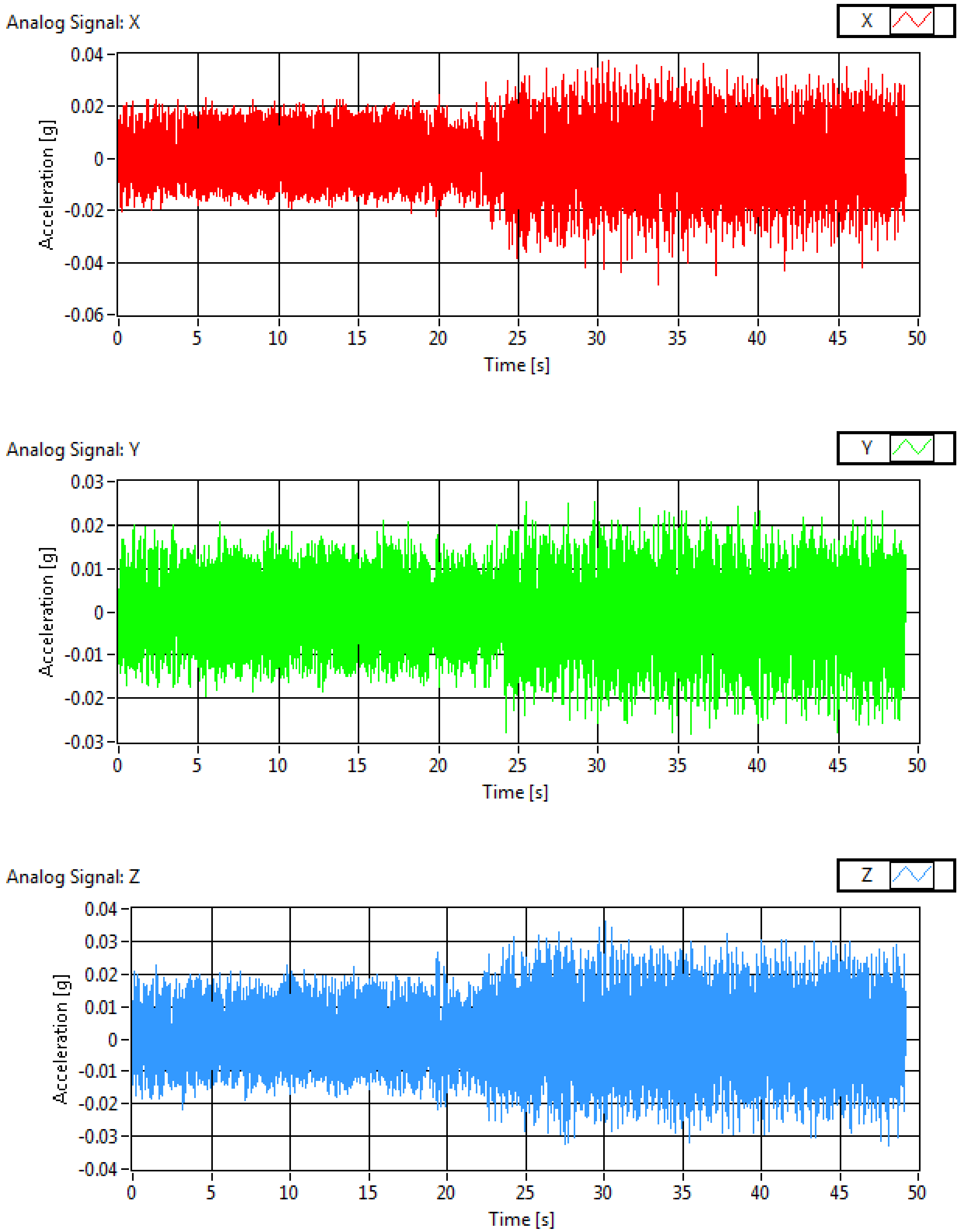


Figure 54 Sterling FD test 09, analog acceleration signals

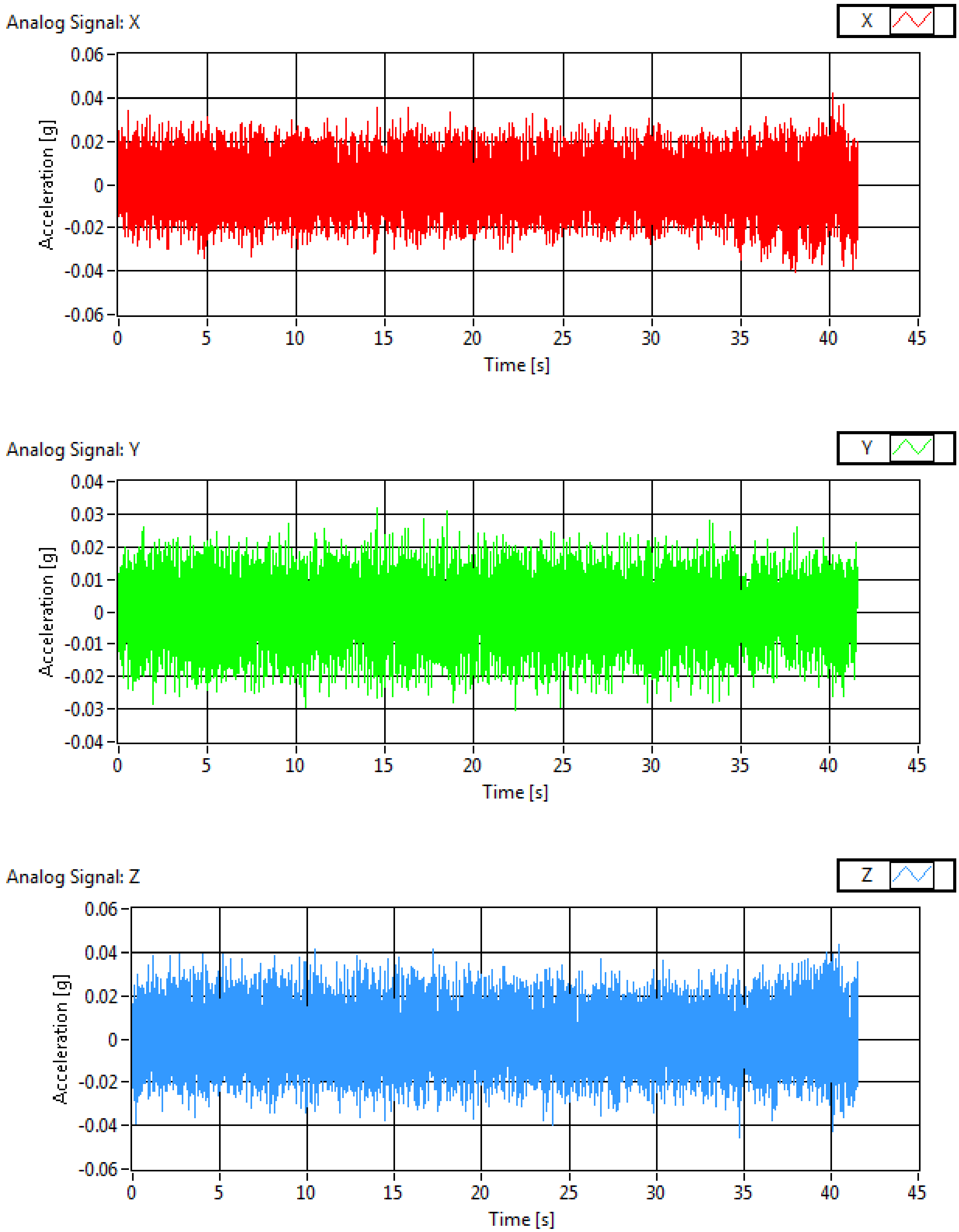


Figure 55 Sterling FD test 10, analog acceleration signals

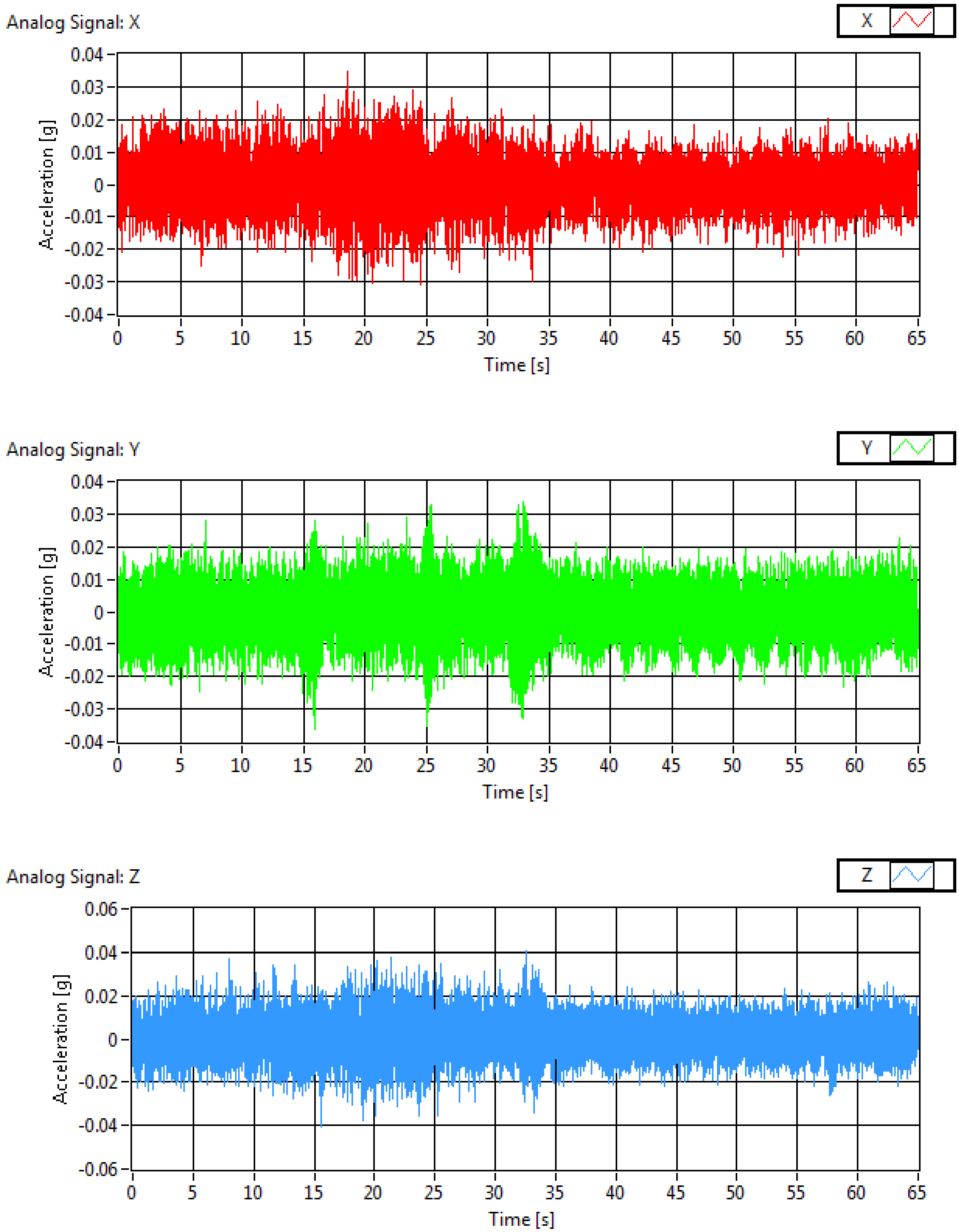


Figure 56 Sterling FD test 11, analog acceleration signals

3.4.2.4 Engine 2 Type (a) Test

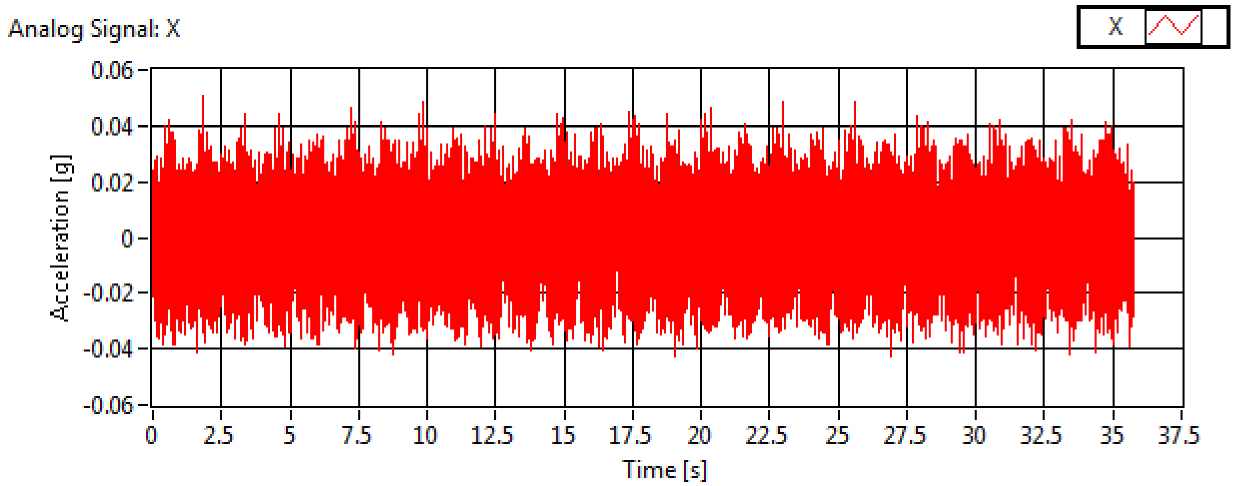
The type (a) test of Sterling Engine 2 was conducted in the driver's-side cabinet over the rear axle. Refer to Figure 57 and Figure 58 for the position of the sensor. Two tests were conducted at this location and recorded as tests 12 and 13. The maximum accelerations of these tests can be seen in Table 18. Raw signal graphs of the analog waveform for each test can be seen in Figure 59 and Figure 60.

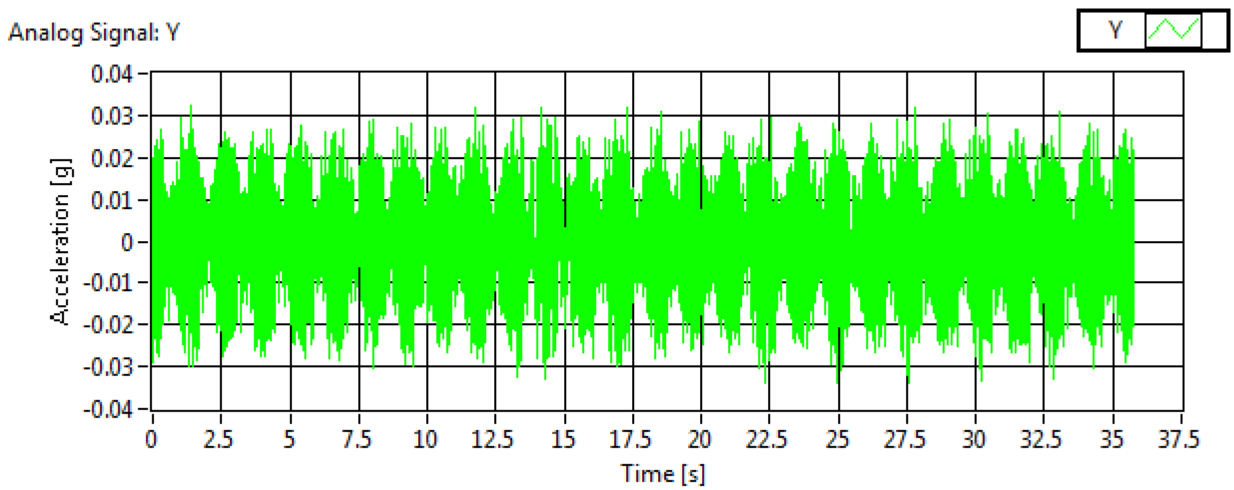
Table 18 Engine 2 type (a) test maximum accelerations

Test No.	X-axis max [g]	Y-axis max [g]	Z-axis max [g]
12	+ 0.05039 / - 0.04308	+ 0.03236 / - 0.03383	+ 0.03429 / - 0.04035
13	+ 0.05074 / - 0.04436	+ 0.03235 / - 0.03545	+ 0.03653 / - 0.04085

Figure 57 Location of sensor for test (a) of Engine 2

Figure 58 Location of sensor for test (a) of Engine 2 (circled)





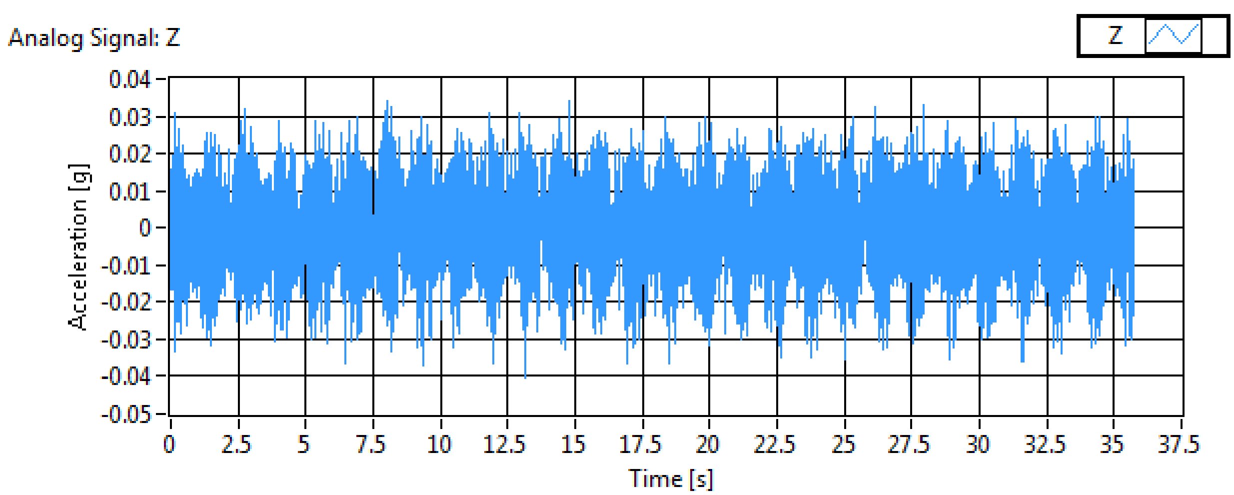


Figure 59 Sterling FD test 12, analog acceleration signals

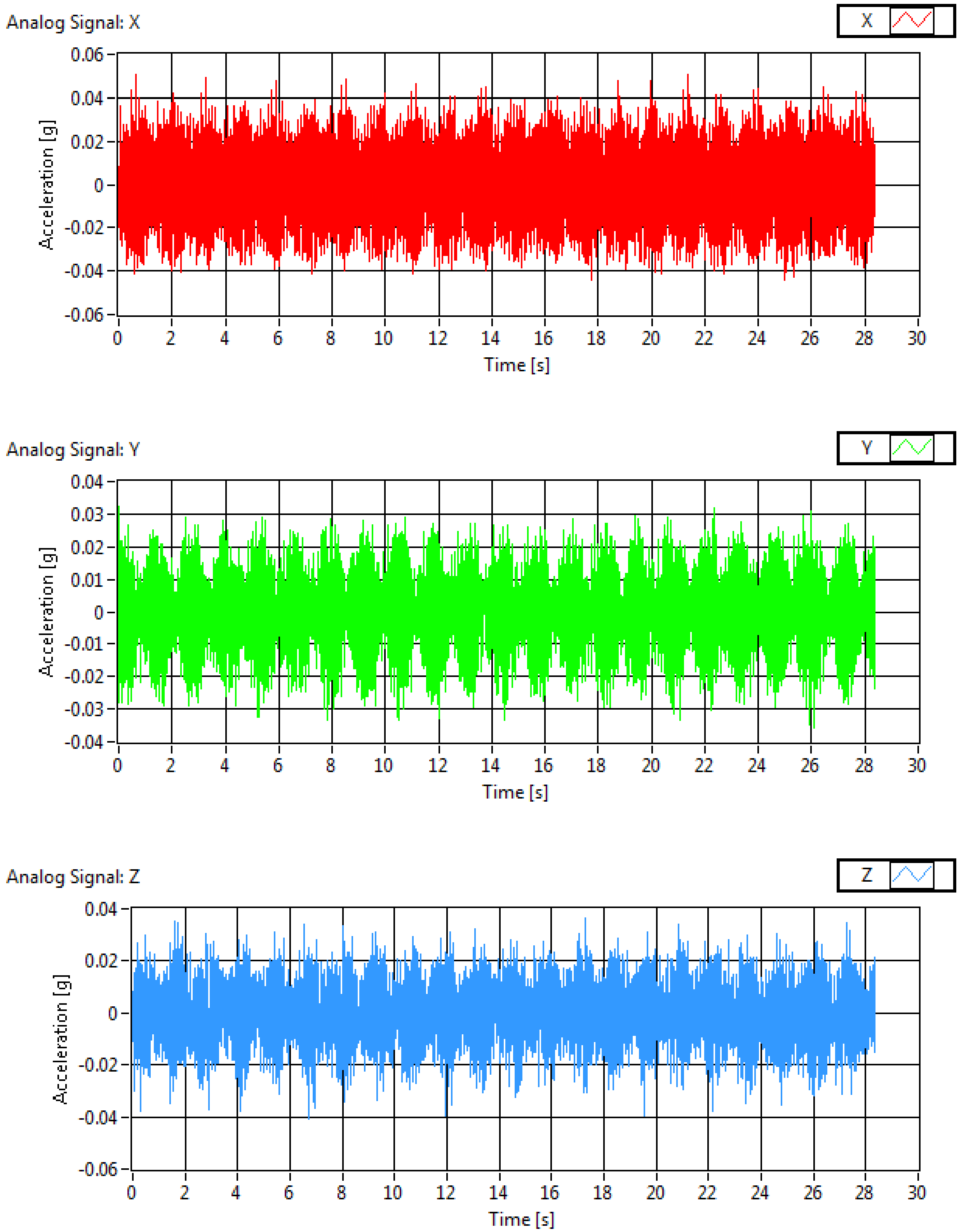


Figure 60 Sterling FD test 13, analog acceleration signals

3.4.2.5 Engine 2 Type (c) Test

Firefighters on scene indicated that the auxiliary power generator in the officer's side compartment of Engine 2 generated a large amount of vibration. It was their recommendation that recordings be taken at the location. Thus the type (c) test of Sterling Engine 2 was conducted in the officer's-side cabinet between the pump outlets and the rear axle. Refer to Figure 61 and Figure 62 for the position of the sensor. Five tests were conducted at this location and recorded as tests 14, 15, 16, 18, and 19. The maximum accelerations of these tests can be seen in Table 19. Raw signal graphs of the analog waveform for each test can be seen in Figure 63 through Figure 67.

Table 19 Engine 2 type (c) test maximum accelerations

Test No.	X-axis max [g]	Y-axis max [g]	Z-axis max [g]
14	+ 0.13931 / - 0.11990	+ 0.17563 / - 0.15744	+ 0.17587 / - 0.14630
15	+ 0.14248 / - 0.12977	+ 0.17720 / - 0.16555	+ 0.16889 / - 0.14176
16	+ 0.14467 / - 0.12323	+ 0.16878 / - 0.17290	+ 0.16481 / - 0.13651
18	+ 0.09222 / - 0.09417	+ 0.12151 / - 0.11955	+ 0.16801 / - 0.18161
19	+ 0.08271 / - 0.08955	+ 0.10411 / - 0.09014	+ 0.09746 / - 0.09573

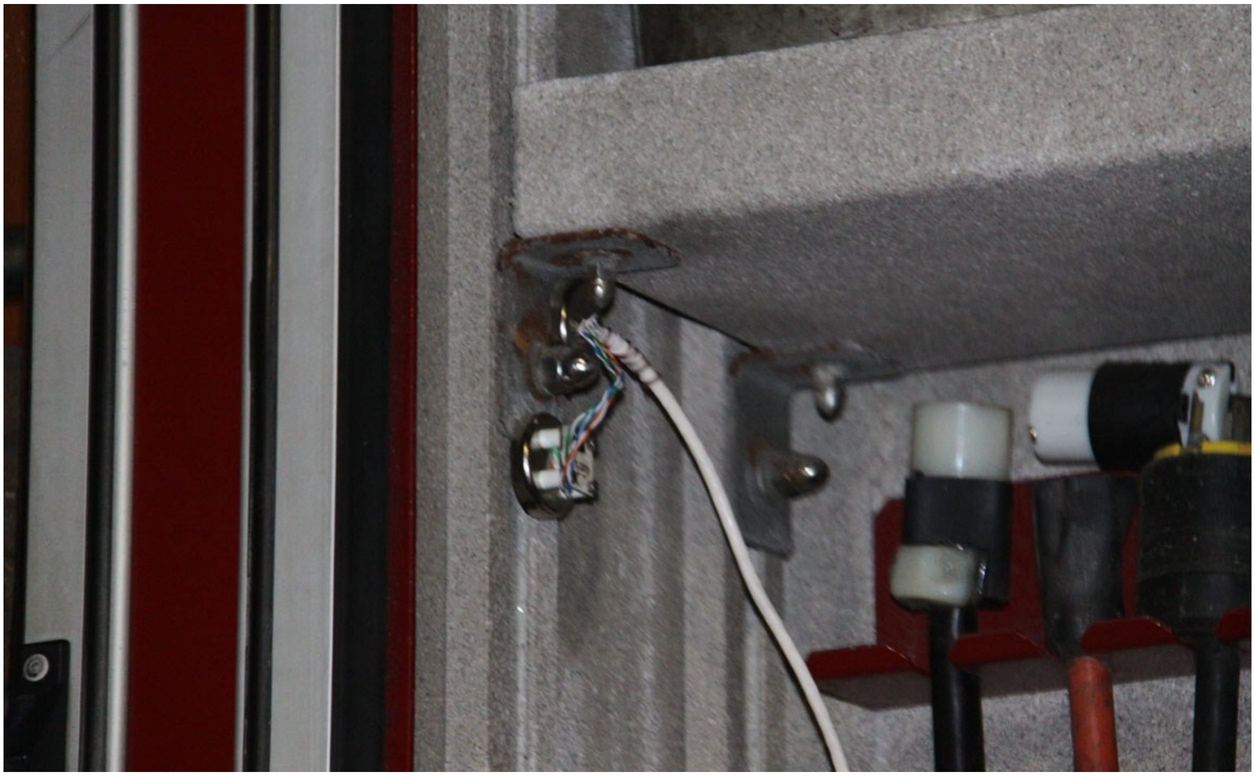
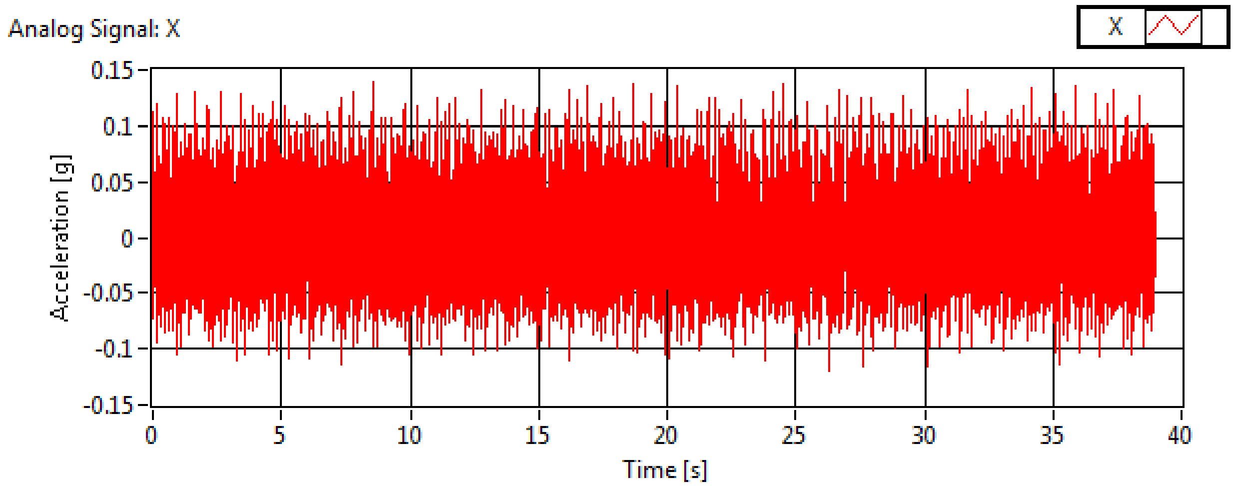
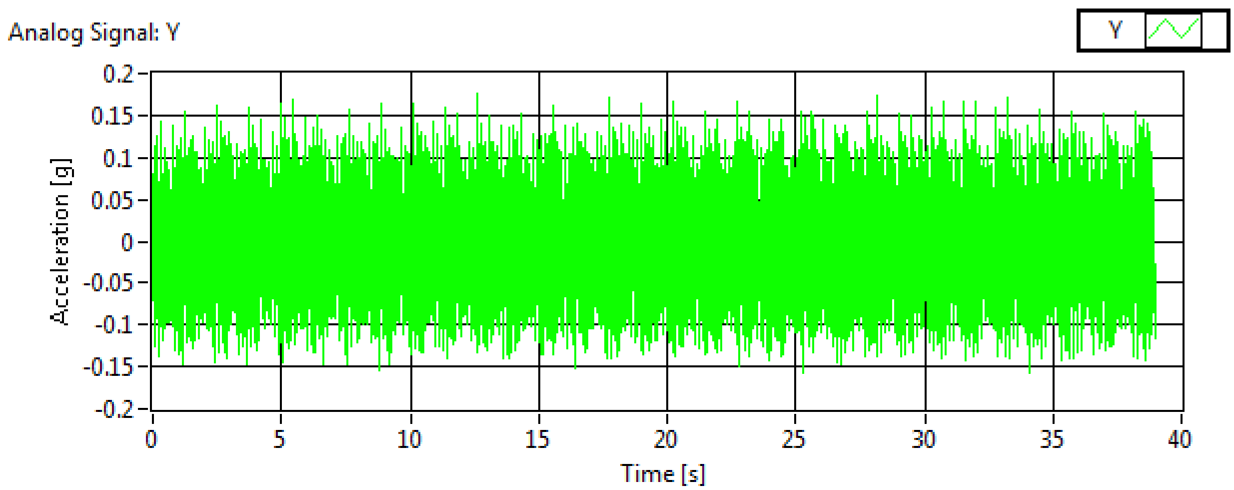


Figure 61 Location of sensor for test (c) of Engine 2

Figure 62 Location of sensor for test (c) of Engine 2 (circled)





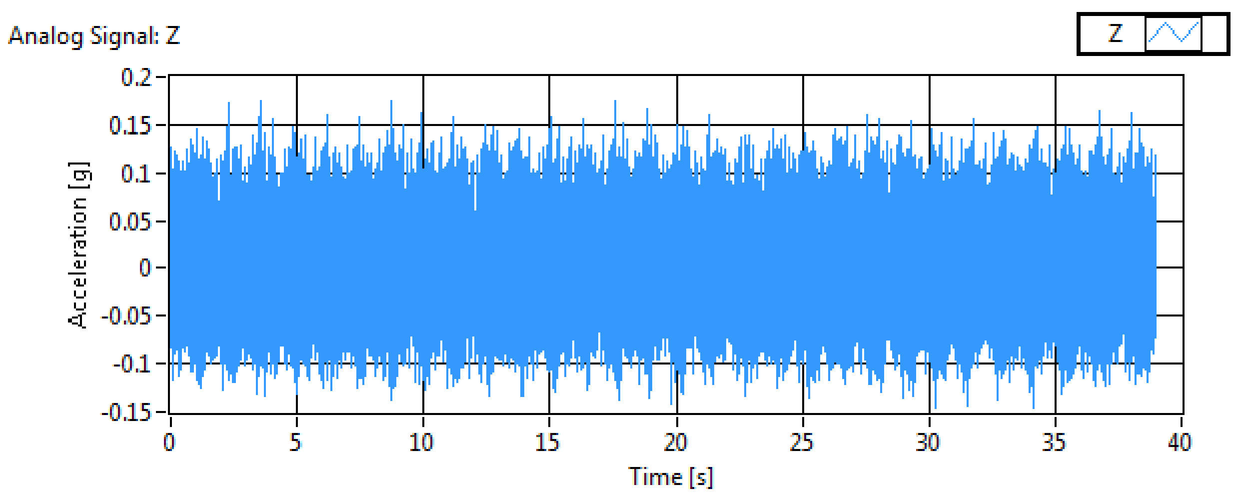


Figure 63 Sterling FD test 14, analog acceleration signals

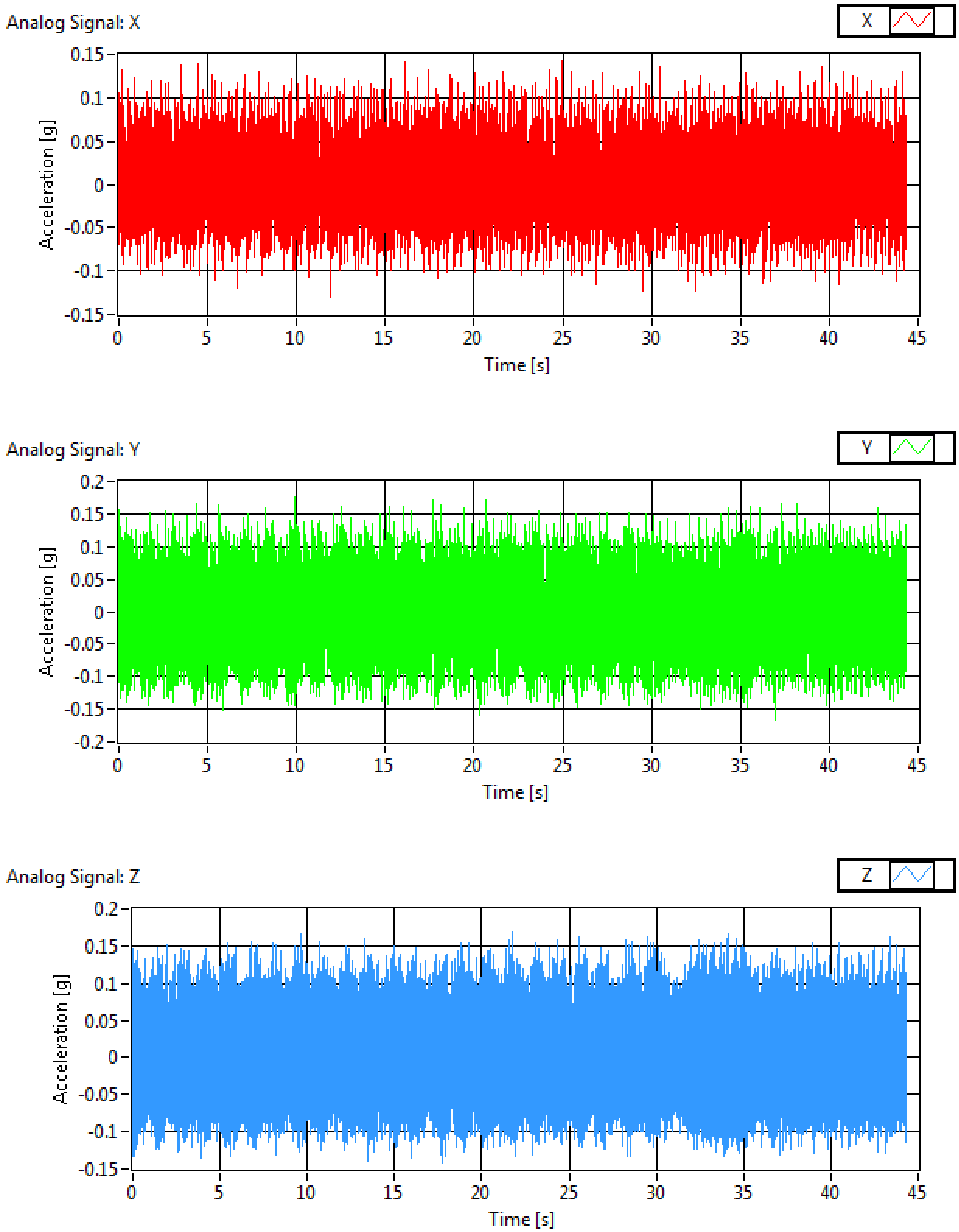


Figure 64 Sterling FD test 15, analog acceleration signals

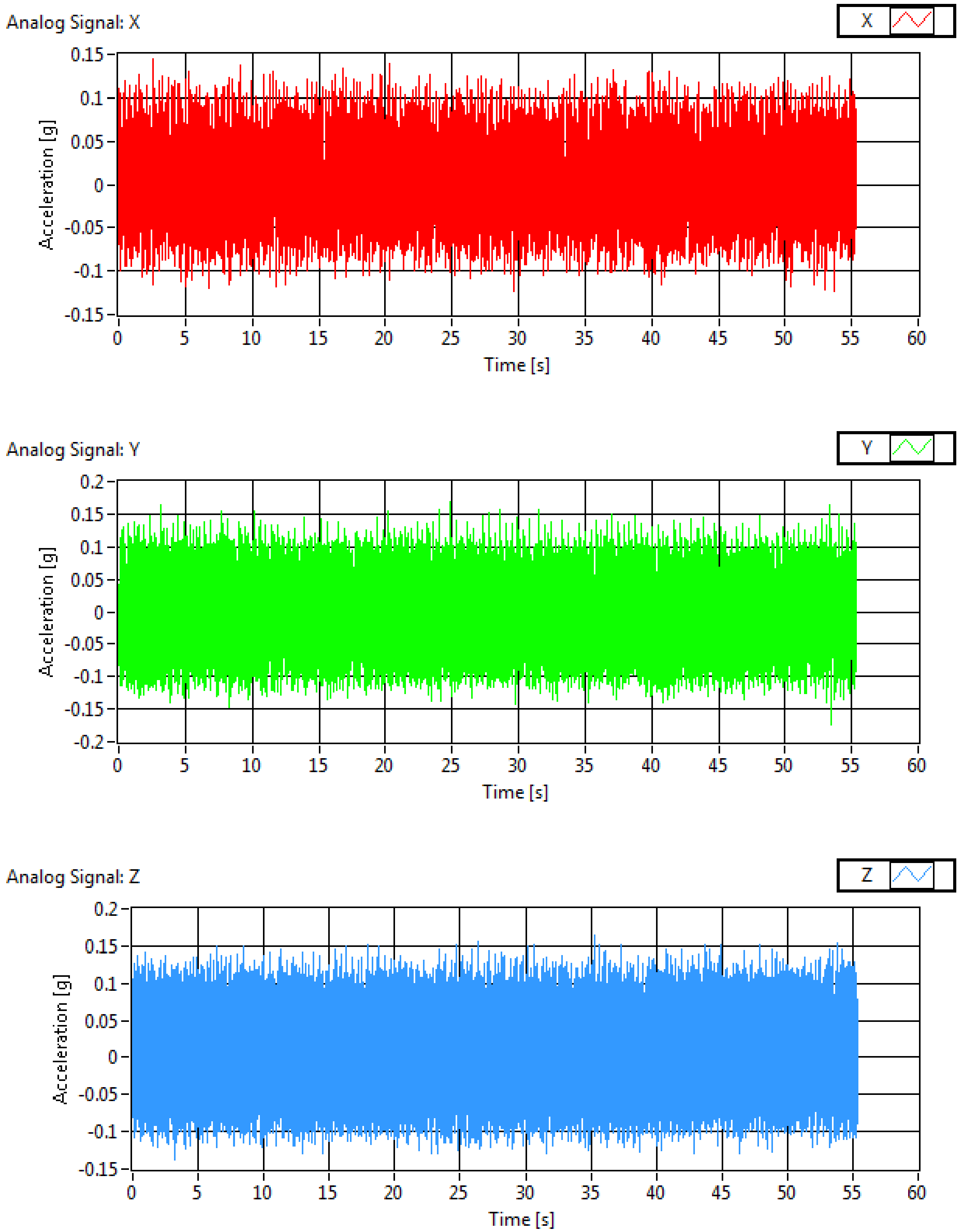


Figure 65 Sterling FD test 16, analog acceleration signals

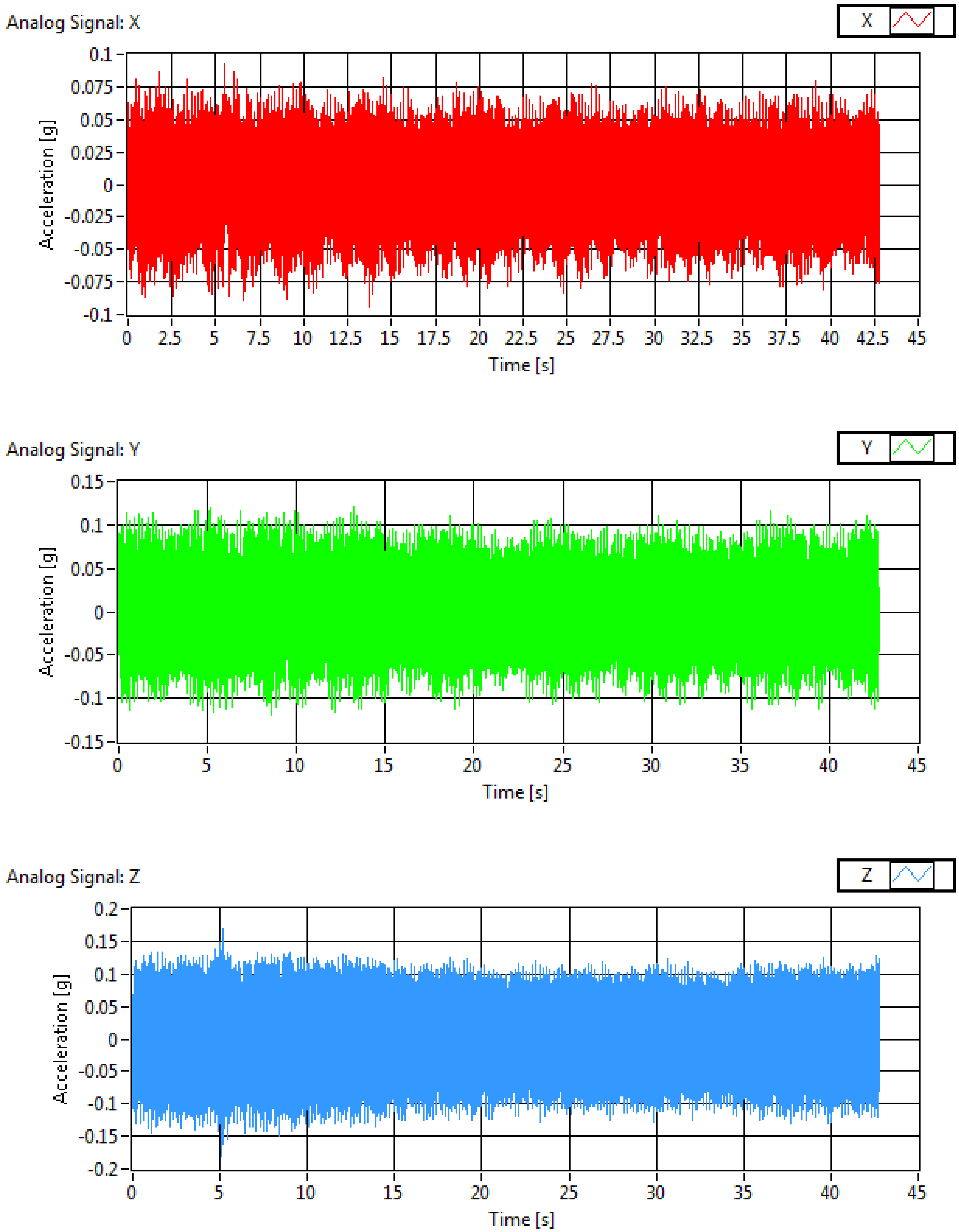


Figure 66 Sterling FD test 18, analog acceleration signals

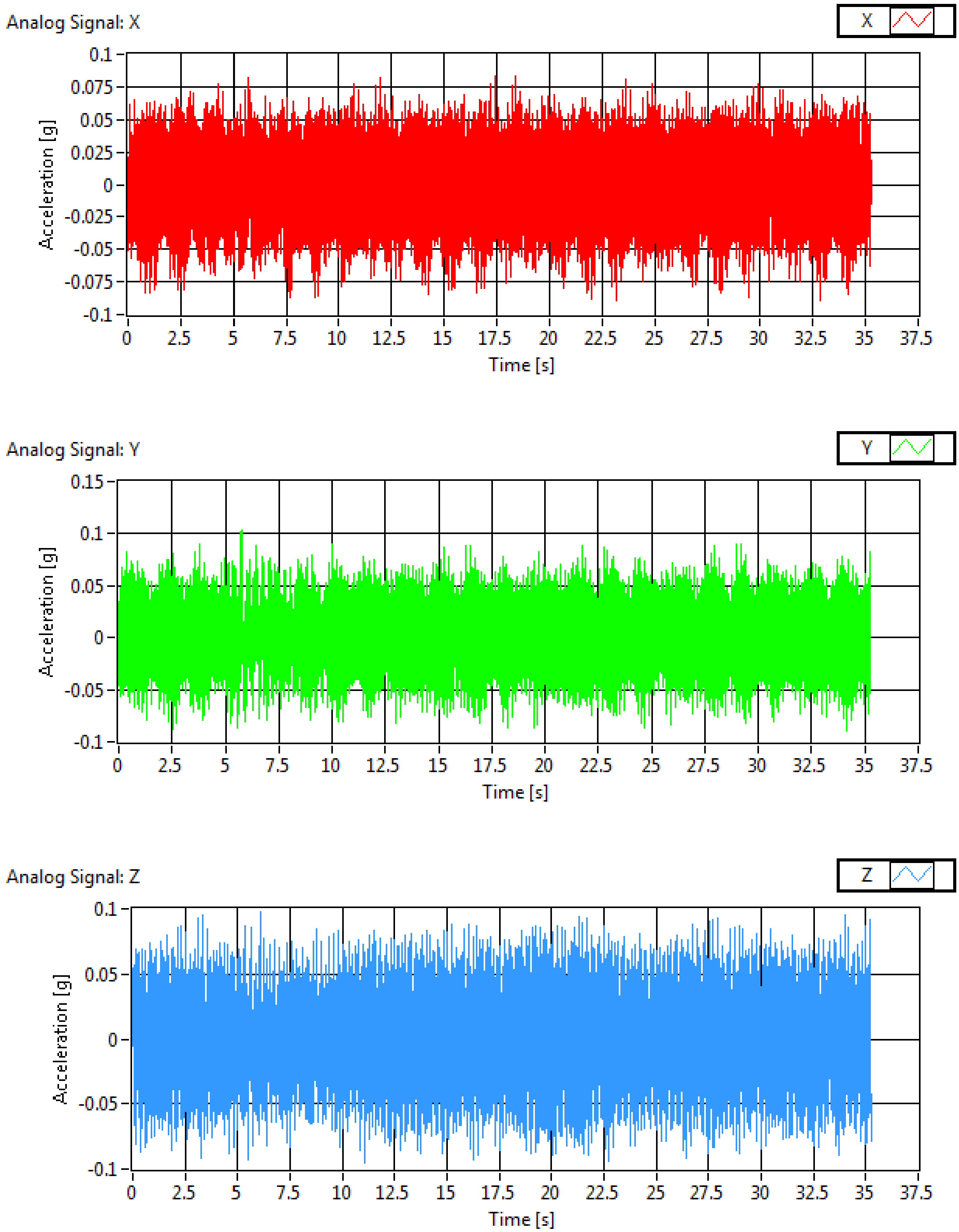


Figure 67 Sterling FD test 19, analog acceleration signals

3.4.2.6 Engine 2 Type (d) Test

The type (d) test of Sterling Engine 2 was conducted on the SCBA frame of the rear driver's side jump seat. Refer to Figure 68 and Figure 69 for the position of the sensor. One test was conducted at this location and recorded as test 20. The maximum accelerations of the test can be seen in Table 20. Raw signal graphs of the analog waveform for each test can be seen in Figure 70.

Table 20 Engine 4 type (d) test maximum accelerations

Test No.	X-axis max [g]	Y-axis max [g]	Z-axis max [g]
20	+ 0.16994 / - 0.15448	+ 0.02613 / - 0.02337	+ 0.13433 / - 0.09838

Figure 68 Location of sensor for test (d) of Engine 2

Figure 69 Location of sensor for test (d) of Engine 2 (circled)

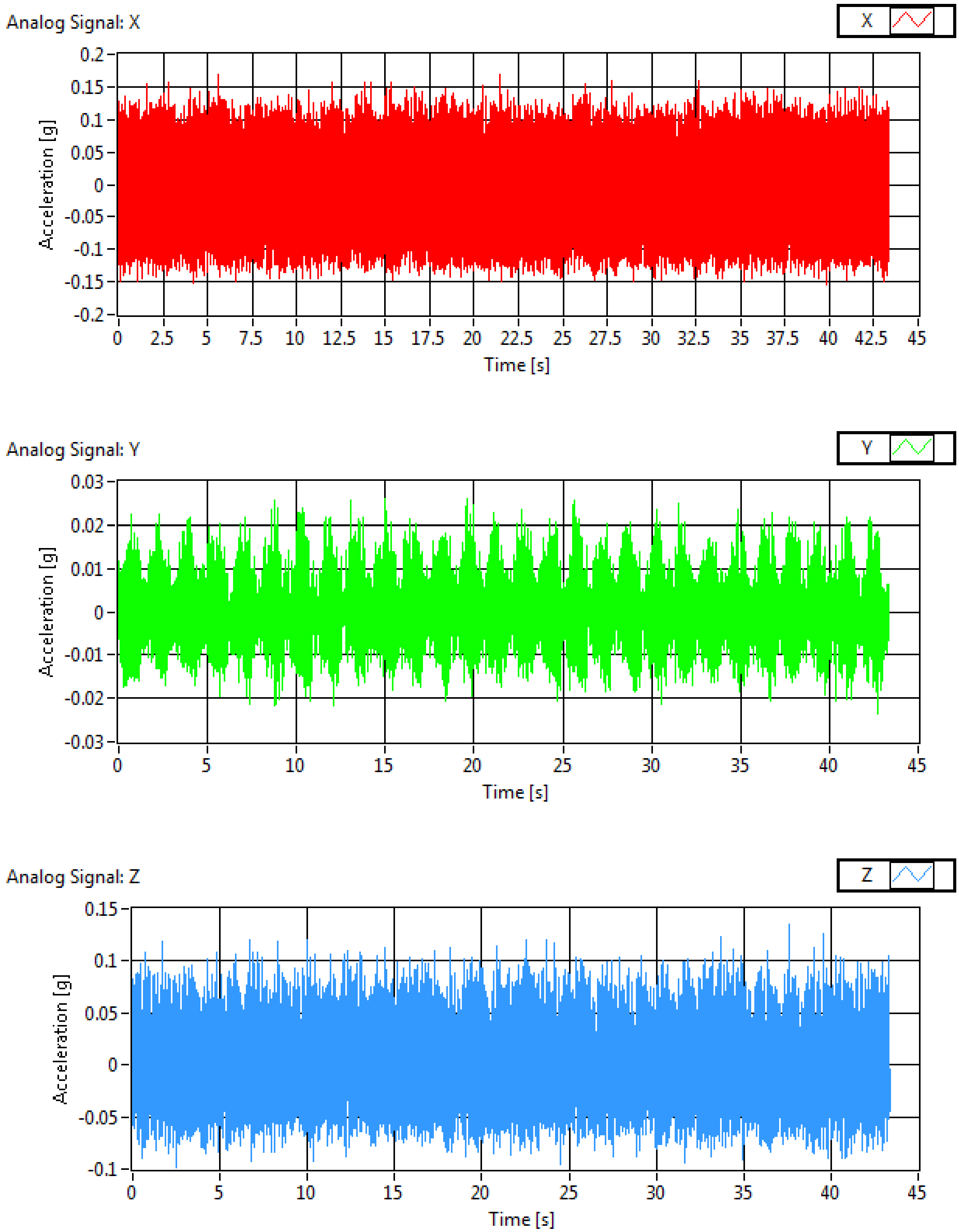


Figure 70 Sterling FD test 20, analog acceleration signals

3.4.2.7 Engine 2 Type (e) Test

The type (e) test of Sterling Engine 2 was conducted on the chassis of the apparatus. The box-beams were easily accessible due to the positioning of the central pump panel. Refer to Figure 71 and Figure 72 for the position of the sensor. One test was conducted at this location and recorded as test 21. The maximum accelerations of the test can be seen in Table 21. Raw signal graphs of the analog waveform for each test can be seen in Figure 73.

Table 21 Engine 4 type (e) test maximum accelerations

Test No.	X-axis max [g]	Y-axis max [g]	Z-axis max [g]
21	+ 0.17351 / - 0.16341	+ 0.02763 / - 0.02618	+ 0.13464 / - 0.09971

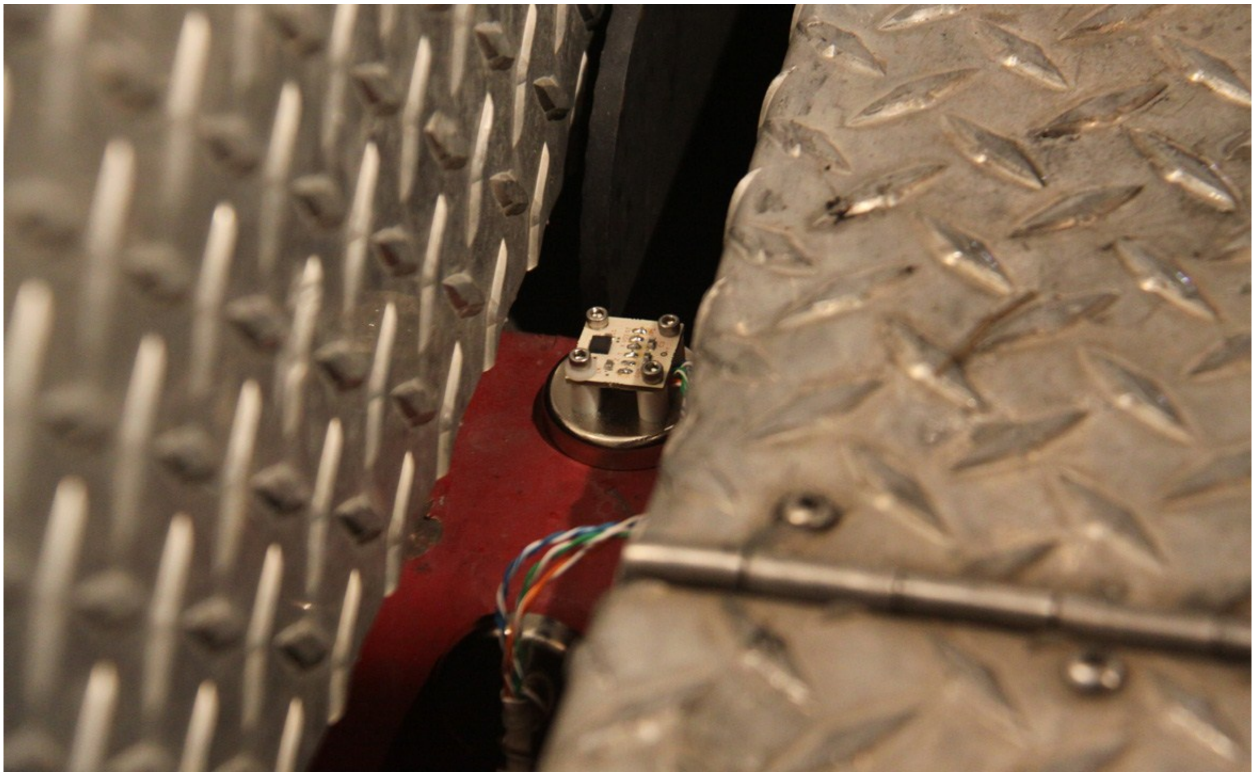


Figure 71 Location of sensor for test (e) of Engine 2

Figure 72 Location of sensor for test (e) of Engine 2 (circled)

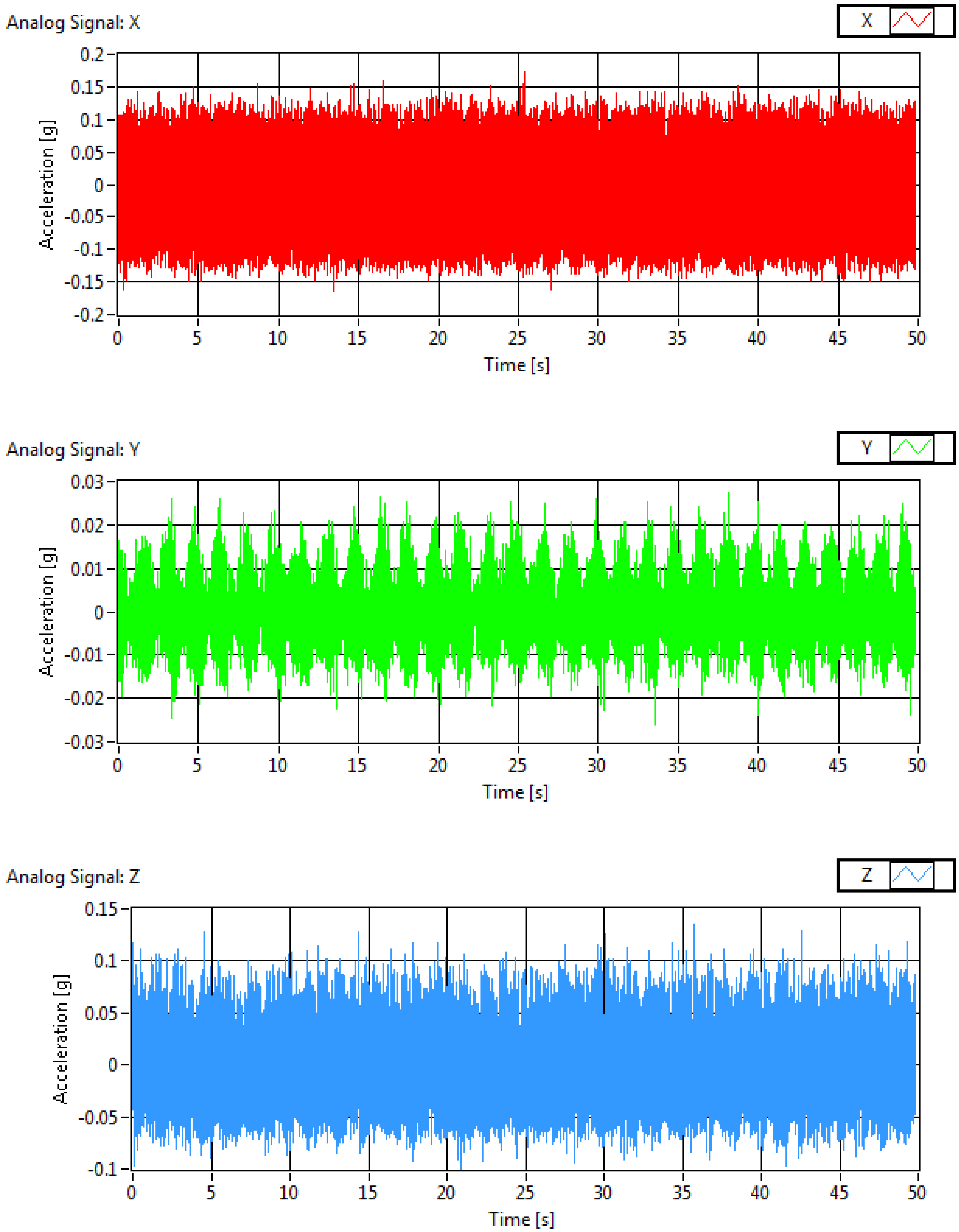


Figure 73 Sterling FD test 21, analog acceleration signals

3.5 Data Analysis

3.5.1 Spectral Transformations

Spectral analysis of the given data was calculated using the LabView Playback02 virtual instrument. The following sections contain peak spectral content, spectrograms, and fast Fourier transforms of the various tests. From the spectrograms, steady-state conditions can be quickly determined by eye. It is over these steady state conditions that the FFT's are performed. This technique ensures that steady and consistent data is used for the transform process, thus generating a meaningful spectrum of amplitudes. The top four peaks of the spectrums of the x-, y-, and z-axes are then listed at the beginning of the particular tests. The pages for the test types are as follows:

3.5.1.1 Engine 4 Type (a) Test

Table 22 Engine 4 type (a) test spectral peaks, x-axis

Test	First Peak, X		Second Peak, X		Third Peak, X		Fourth Peak, X	
No.	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]
01	3.4	0.00340	1.6	0.00120	0.2	0.00110	6.8	0.00080
02	34.8	0.00480	35.4	0.00140	11.8	0.00070	17.4	0.00060
03	35.0	0.00360	11.8	0.00090	29.8	0.00070	17.4	0.00060

Table 23 Engine 4 type (a) test spectral peaks, y-axis

Test	First Peak, Y		Second Peak, Y		Third Peak, Y		Fourth Peak, Y	
No.	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]
01	3.4	0.00280	2.2	0.00190	0.6	0.00080	7.0	0.00070
02	34.8	0.00330	11.8	0.00180	35.4	0.00120	21.2	0.00110
03	35.0	0.00390	11.8	0.00220	19.6	0.00080	23.4	0.00070

Table 24 Engine 4 type (a) test spectral peaks, z-axis

Test	First Peak, Z		Second Peak, Z		Third Peak, Z		Fourth Peak, Z	
No.	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]
01	3.4	0.00660	13.2	0.00330	9.2	0.00310	14.0	0.00300
02	34.8	0.00520	35.4	0.00150	6.8	0.00140	19.6	0.00120
03	35.0	0.00600	29.8	0.00250	17.6	0.00160	5.0	0.00140

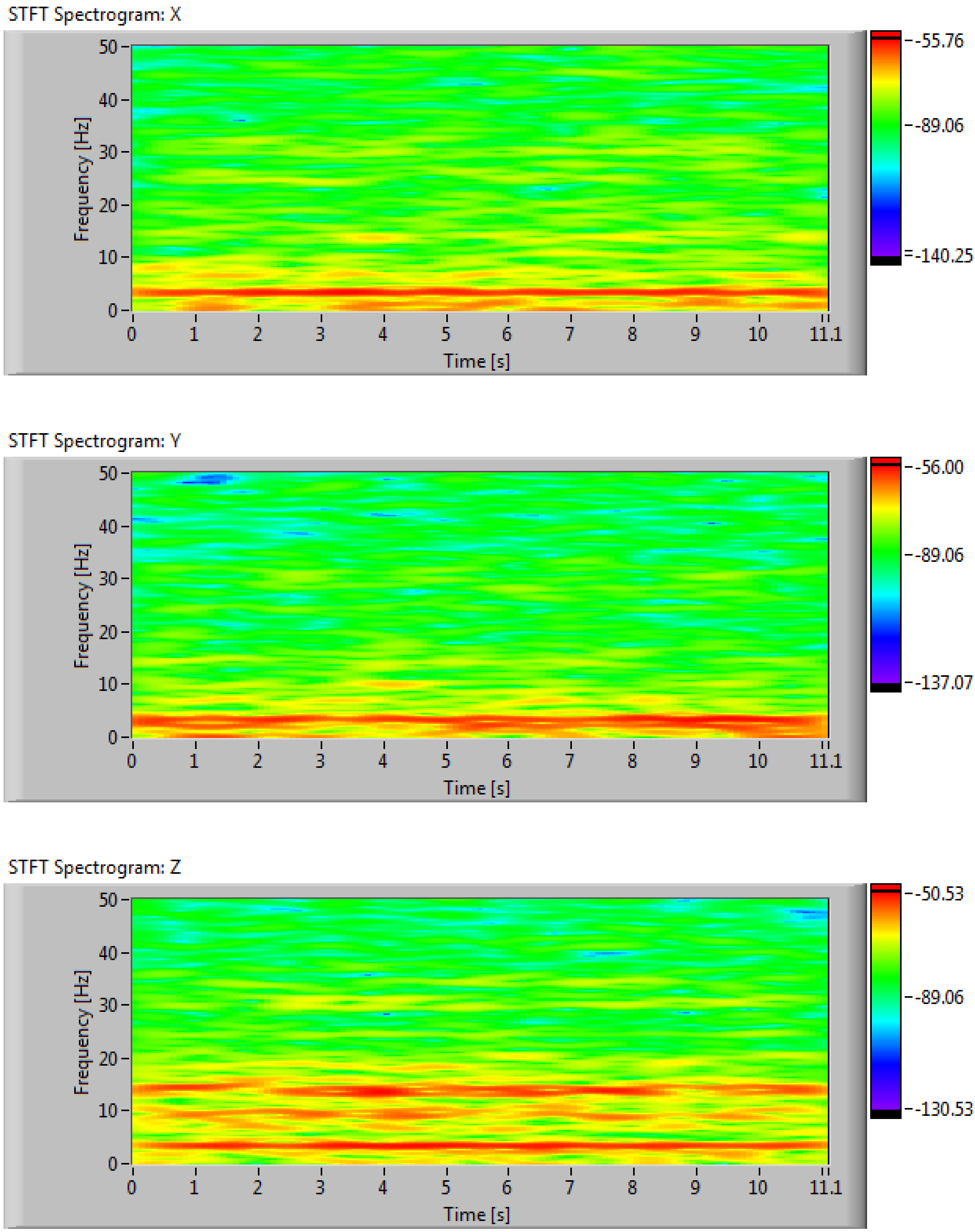


Figure 74 Sterling FD test 01, acceleration spectrogram

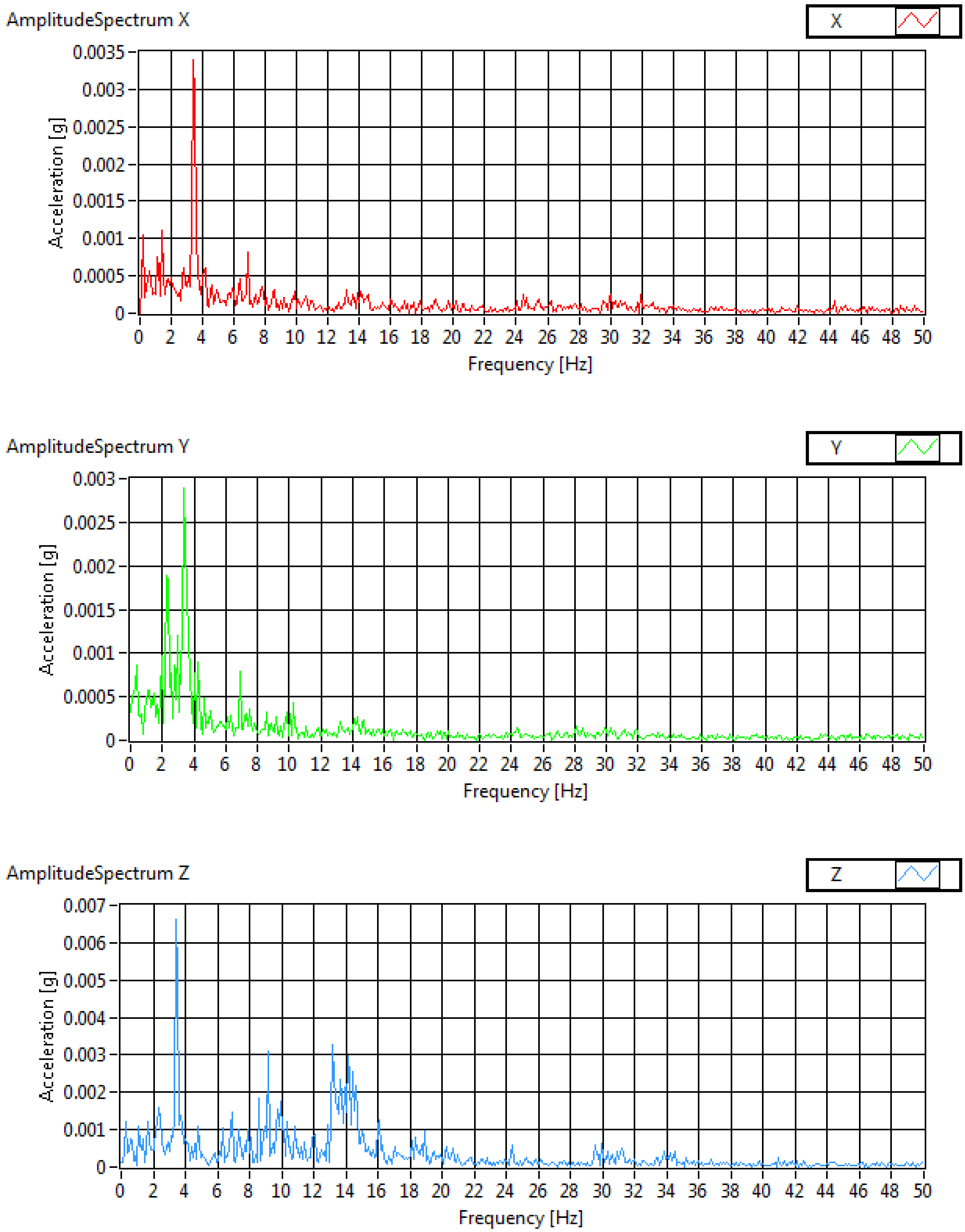


Figure 75 Sterling FD test 01, acceleration spectra

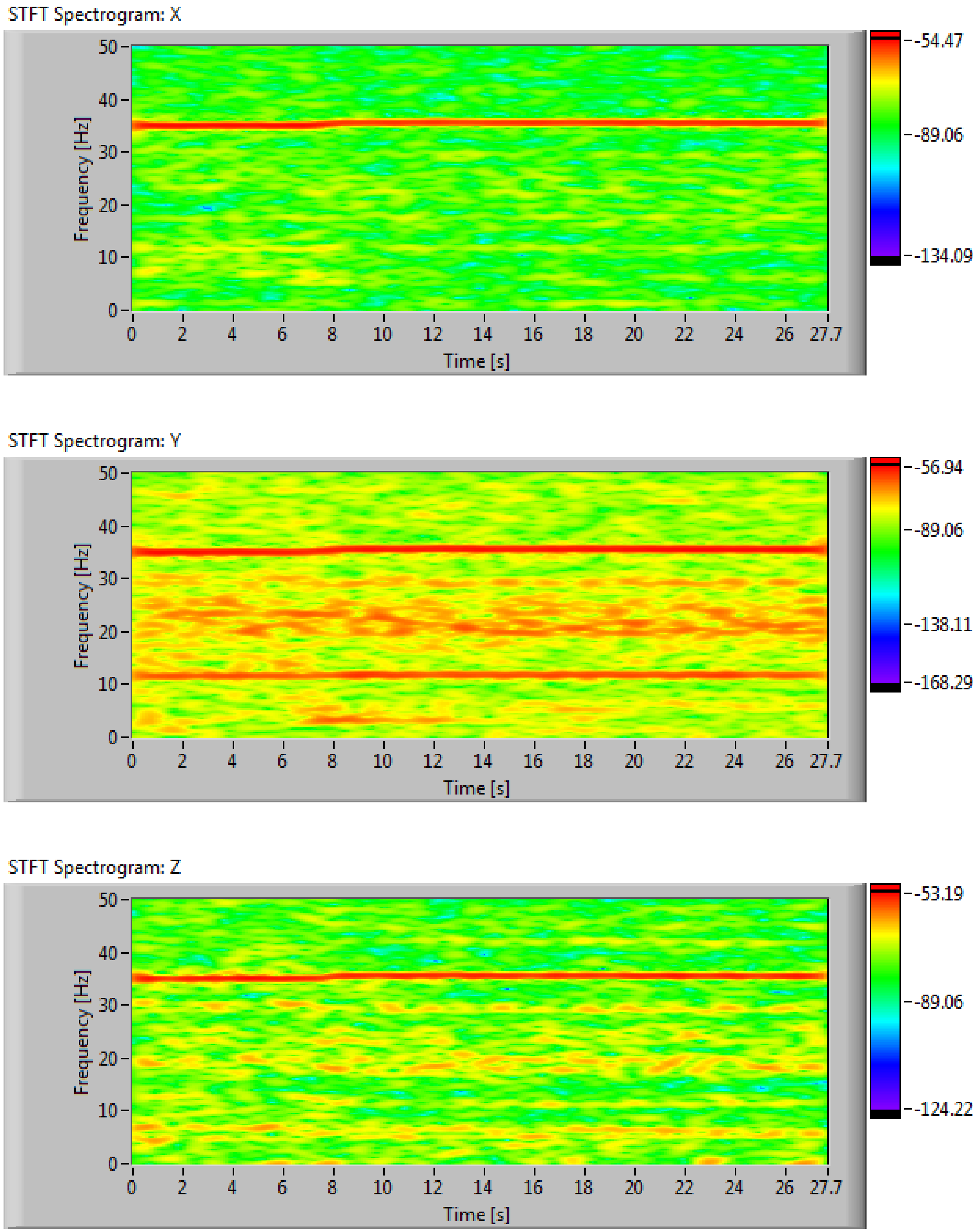


Figure 76 Sterling FD test 02, acceleration spectrogram

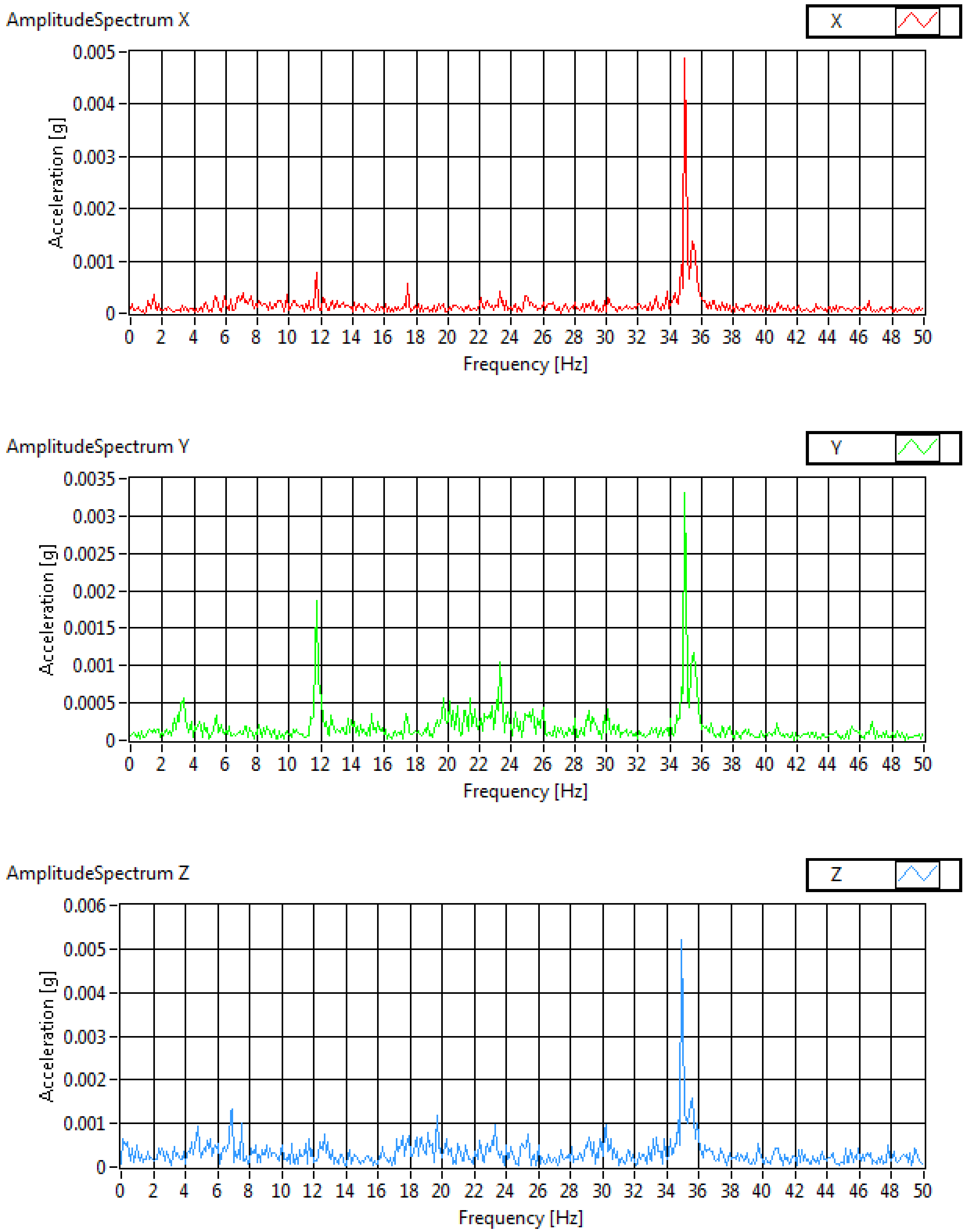


Figure 77 Sterling FD test 02, acceleration spectra

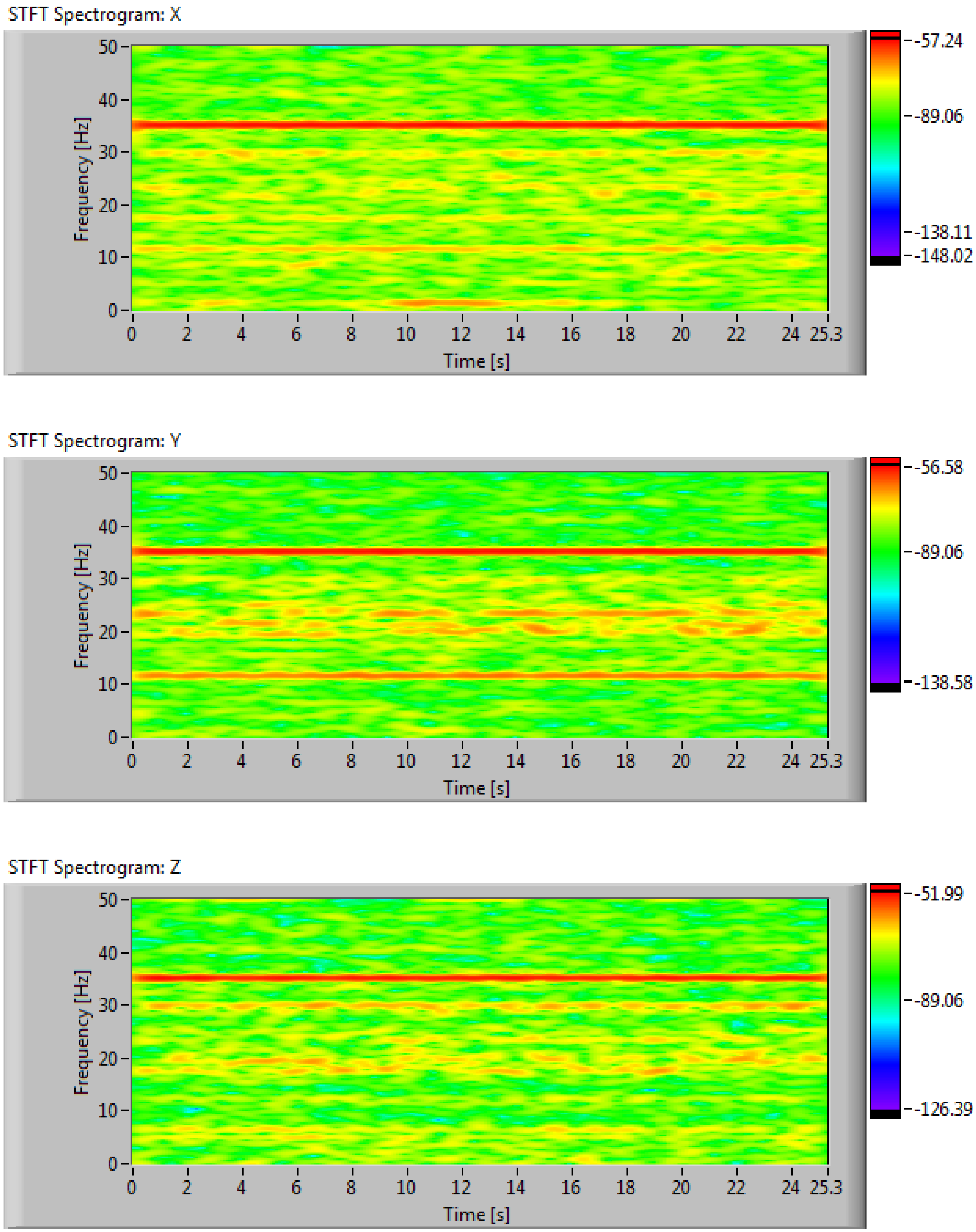
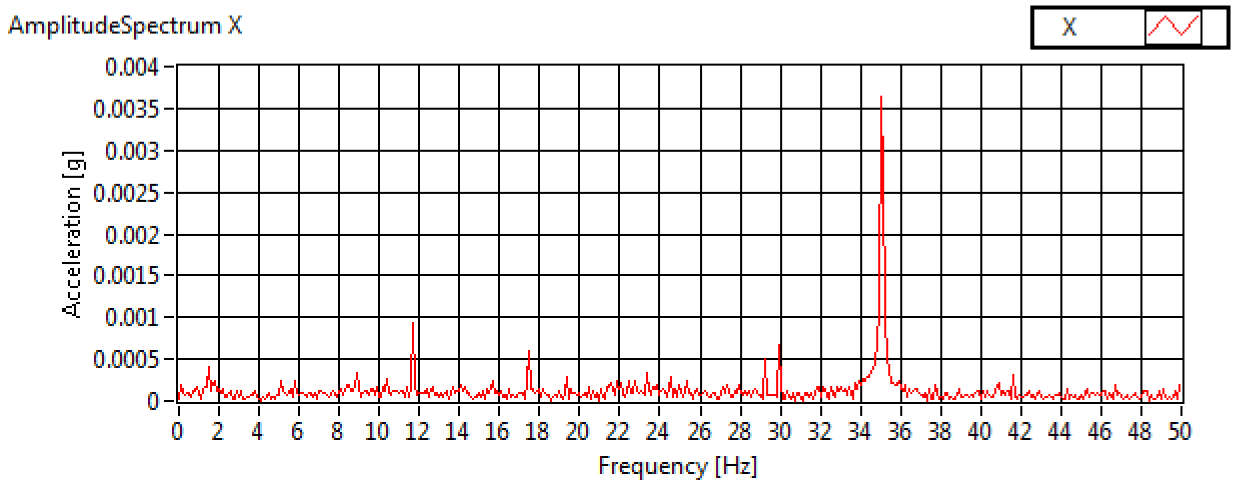
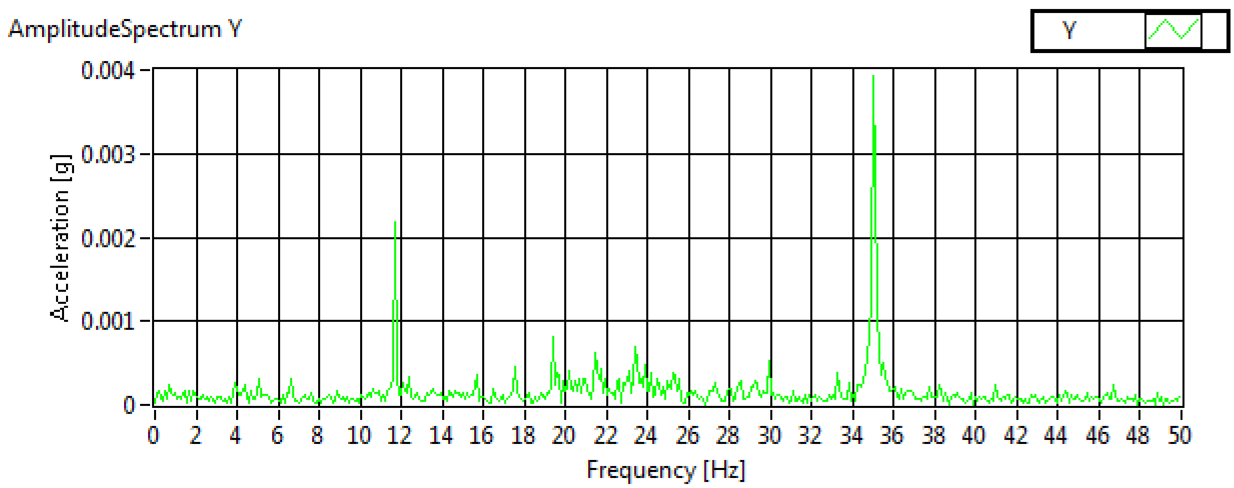


Figure 78 Sterling FD test 03, acceleration spectrogram





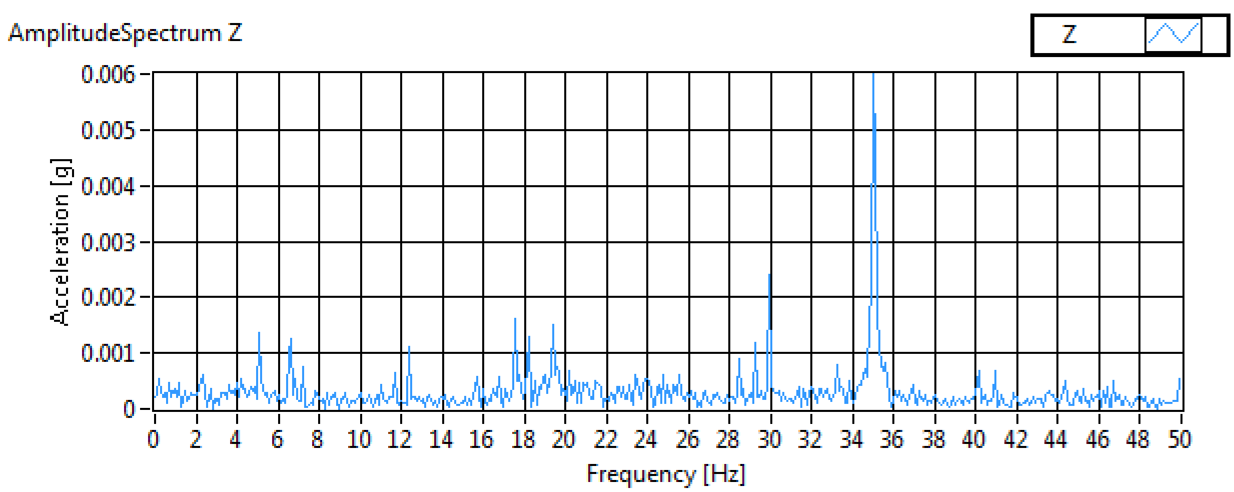


Figure 79 Sterling FD test 03, acceleration spectra

3.5.1.2 Engine 4 Type (b) Test

Table 25 Engine 4 type (b) test spectral peaks, x-axis

Test	First Peak, X		Second Peak, X		Third Peak, X		Fourth Peak, X	
No.	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]
04	35.2	0.01500	11.8	0.00820	41.2	0.00680	47.2	0.00320
04	34.6	0.01750	11.8	0.00900	30.4	0.00550	40.4	0.00450
04	40.6	0.04900	39.2	0.00400	33.6	0.00400	27.0	0.00400
04	42.6	0.07100	28.6	0.00500	21.2	0.00400	35.6	0.00400
05	43.8	0.02800	28.2	0.01200	9.4	0.00400	37.6	0.00350
05	35.4	0.01320	41.2	0.00900	37.2	0.00820	38.4	0.00800
05	41.2	0.07100	38.2	0.00700	27.4	0.00600	20.6	0.00400
06	35.2	0.01600	11.8	0.00750	41.0	0.00400	29.6	0.00250
07	36.4	0.07100	12.2	0.00600	42.8	0.00400	24.6	0.00300
08	35.0	0.02400	40.2	0.00650	11.8	0.00550	30.0	0.00300

Table 26 Engine 4 type (b) test spectral peaks, y-axis

Test	First Peak, Y		Second Peak, Y		Third Peak, Y		Fourth Peak, Y	
No.	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]
04	35.2	0.00920	41.2	0.00580	29.4	0.00500	11.8	0.00380
04	34.6	0.00820	11.8	0.00540	30.4	0.00420	40.4	0.00320
04	40.6	0.04200	20.4	0.00700	19.0	0.00400	13.6	0.00400
04	42.6	0.09200	14.2	0.00800	21.2	0.00600	36.0	0.00400
05	43.8	0.01800	18.6	0.00800	28.2	0.00350	46.8	0.00300
05	35.4	0.00900	41.2	0.00840	40.8	0.00760	38.4	0.00660
05	41.2	0.06900	21.6	0.00600	17.6	0.00500	13.6	0.00400
06	35.2	0.00750	11.8	0.00420	41.0	0.00380	29.6	0.00360
07	36.4	0.04800	42.8	0.00500	12.2	0.00400	18.4	0.00300
08	35.0	0.01900	40.2	0.00300	11.8	0.00250	17.4	0.00250

Table 27 Engine 4 type (b) test spectral peaks, z-axis

Test	First Peak, Z		Second Peak, Z		Third Peak, Z		Fourth Peak, Z	
No.	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]
04	35.2	0.01750	29.4	0.01350	11.8	0.01100	47.2	0.00950
04	30.4	0.01420	11.8	0.01360	34.6	0.00980	38.8	0.00840
04	40.6	0.02100	19.0	0.00900	21.2	0.00800	20.4	0.00800
04	42.6	0.06800	28.2	0.01600	35.2	0.00900	34.8	0.00800
05	43.8	0.08000	40.8	0.01600	28.2	0.01000	46.8	0.00800
05	11.8	0.01240	35.4	0.00980	41.6	0.00920	29.2	0.00780
05	41.2	0.03600	38.2	0.01200	30.4	0.01100	23.6	0.00950
06	35.2	0.01500	11.8	0.01360	29.8	0.01100	41.4	0.00540
07	36.4	0.00720	26.6	0.00660	12.2	0.00580	42.8	0.00560
08	40.2	0.02700	34.2	0.01350	46.0	0.01100	11.8	0.01000

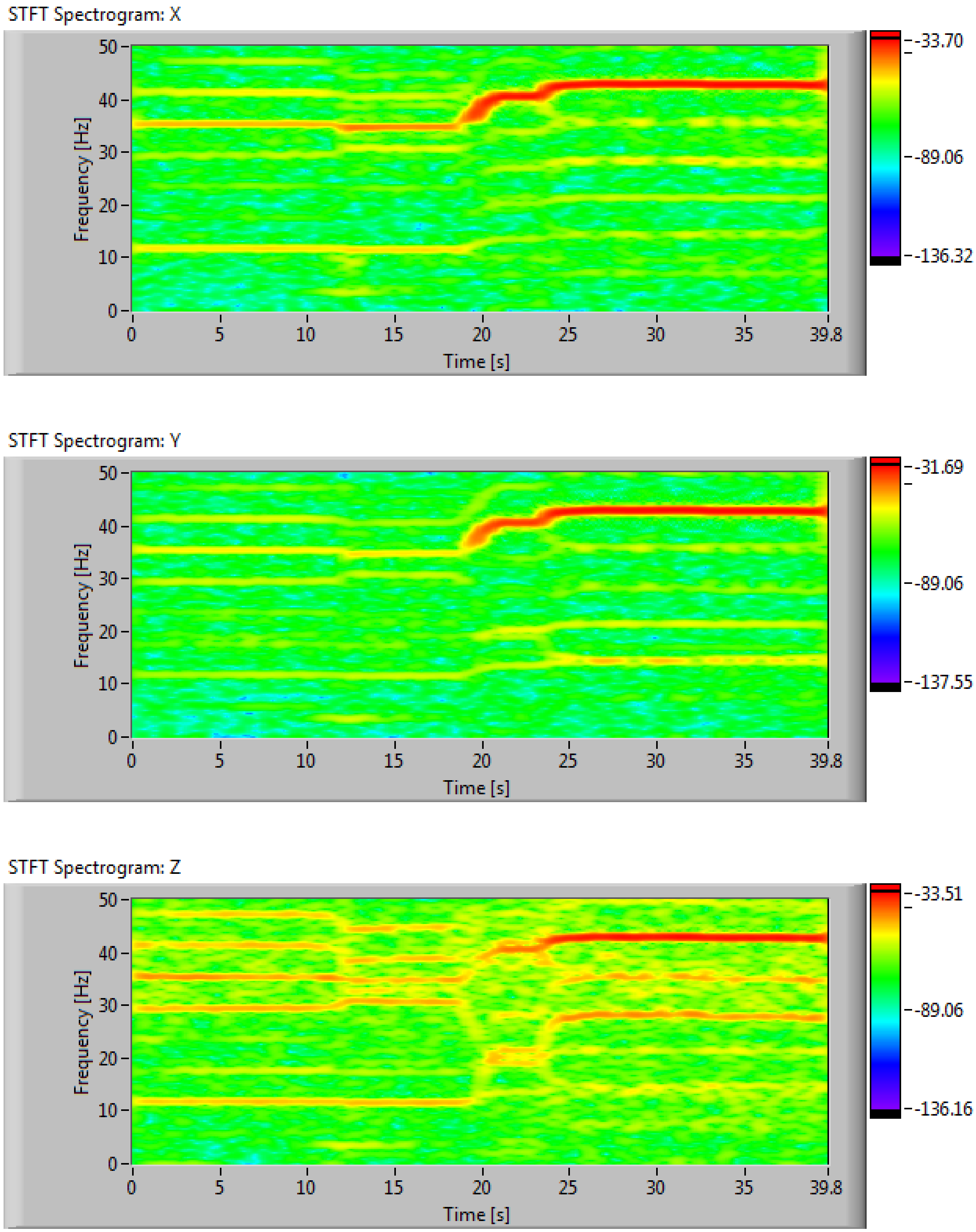


Figure 80 Sterling FD test 04, acceleration spectrogram

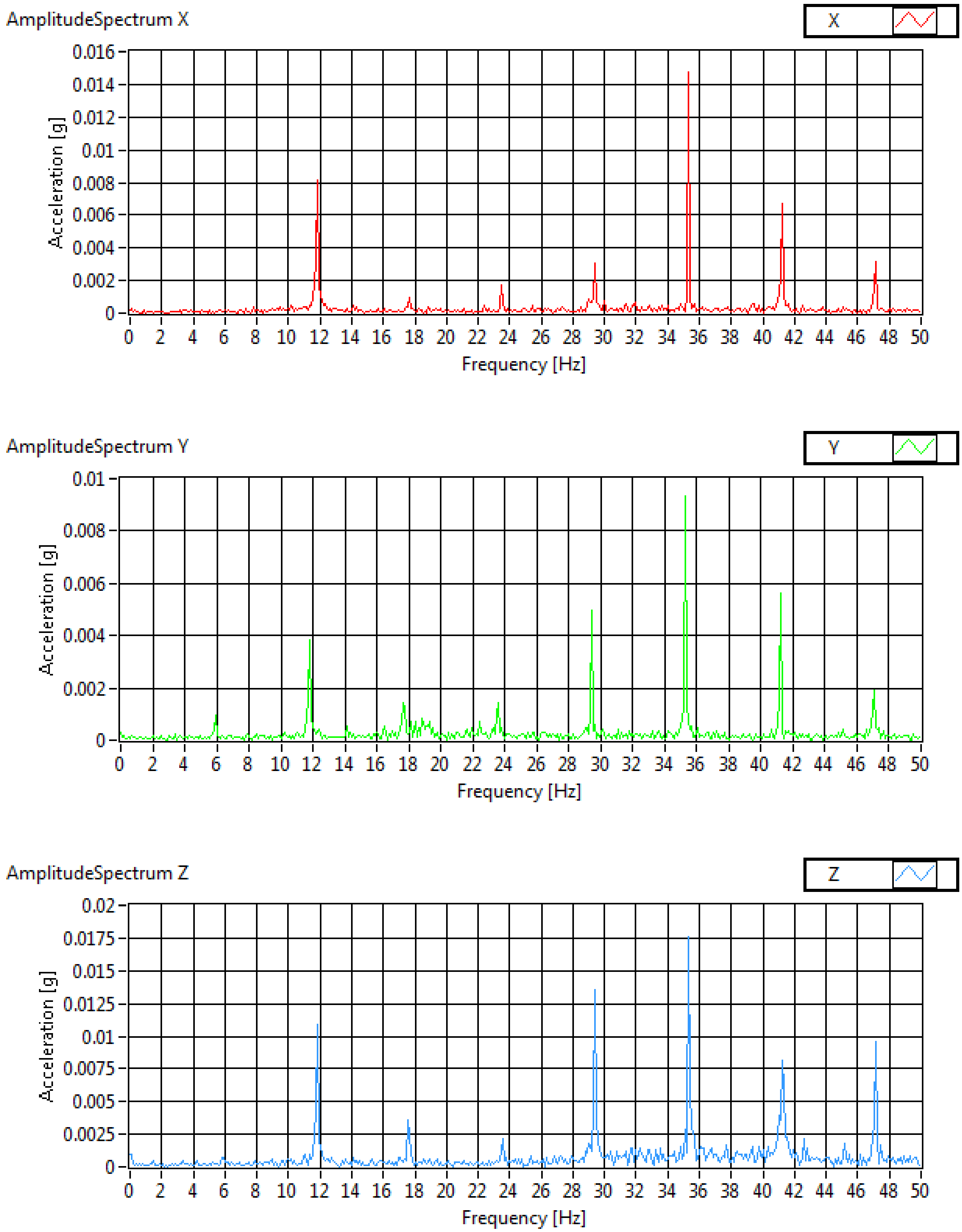


Figure 81 Sterling FD test 04, acceleration spectra (time 0-10)

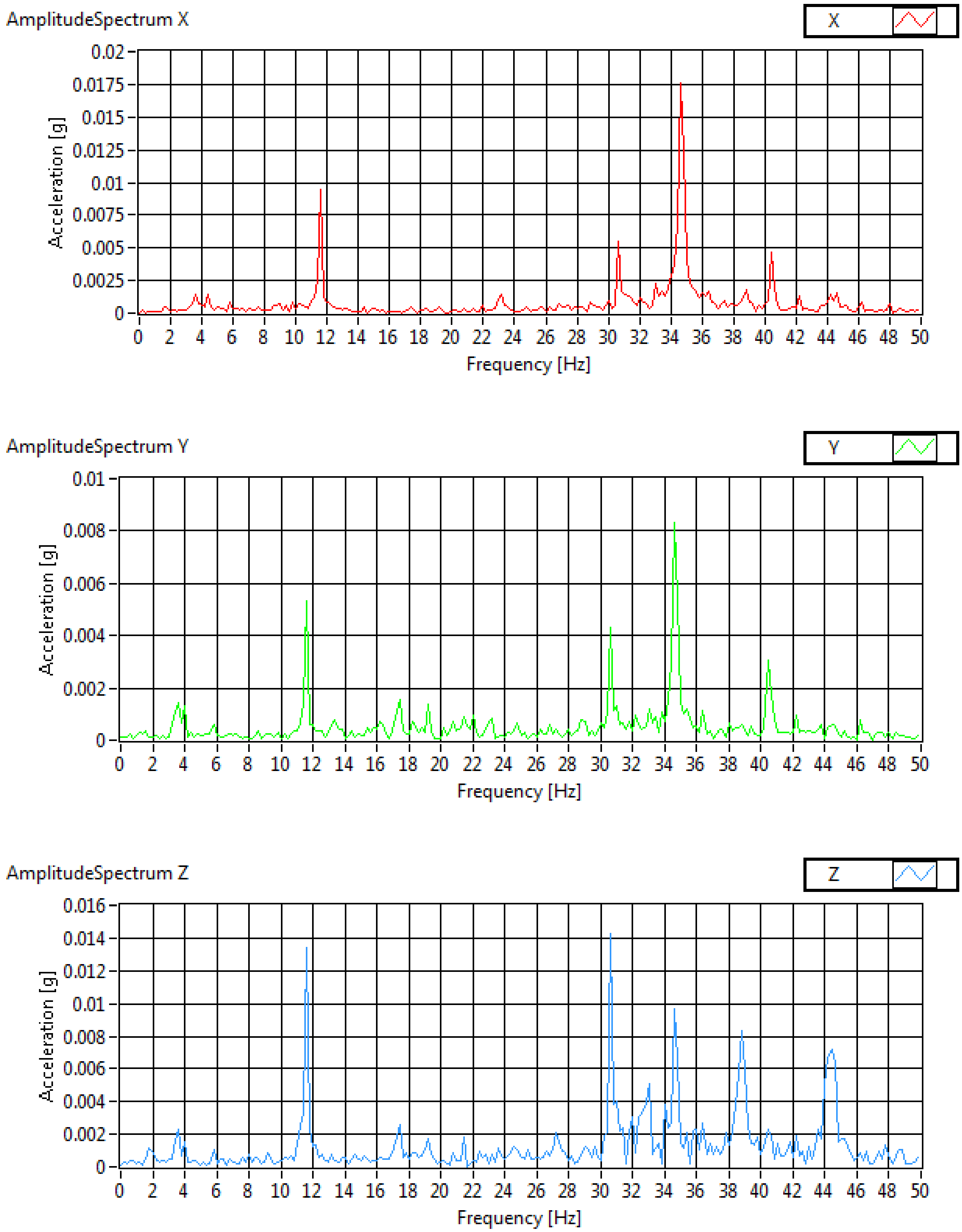


Figure 82 Sterling FD test 04, acceleration spectra (time 13-18)

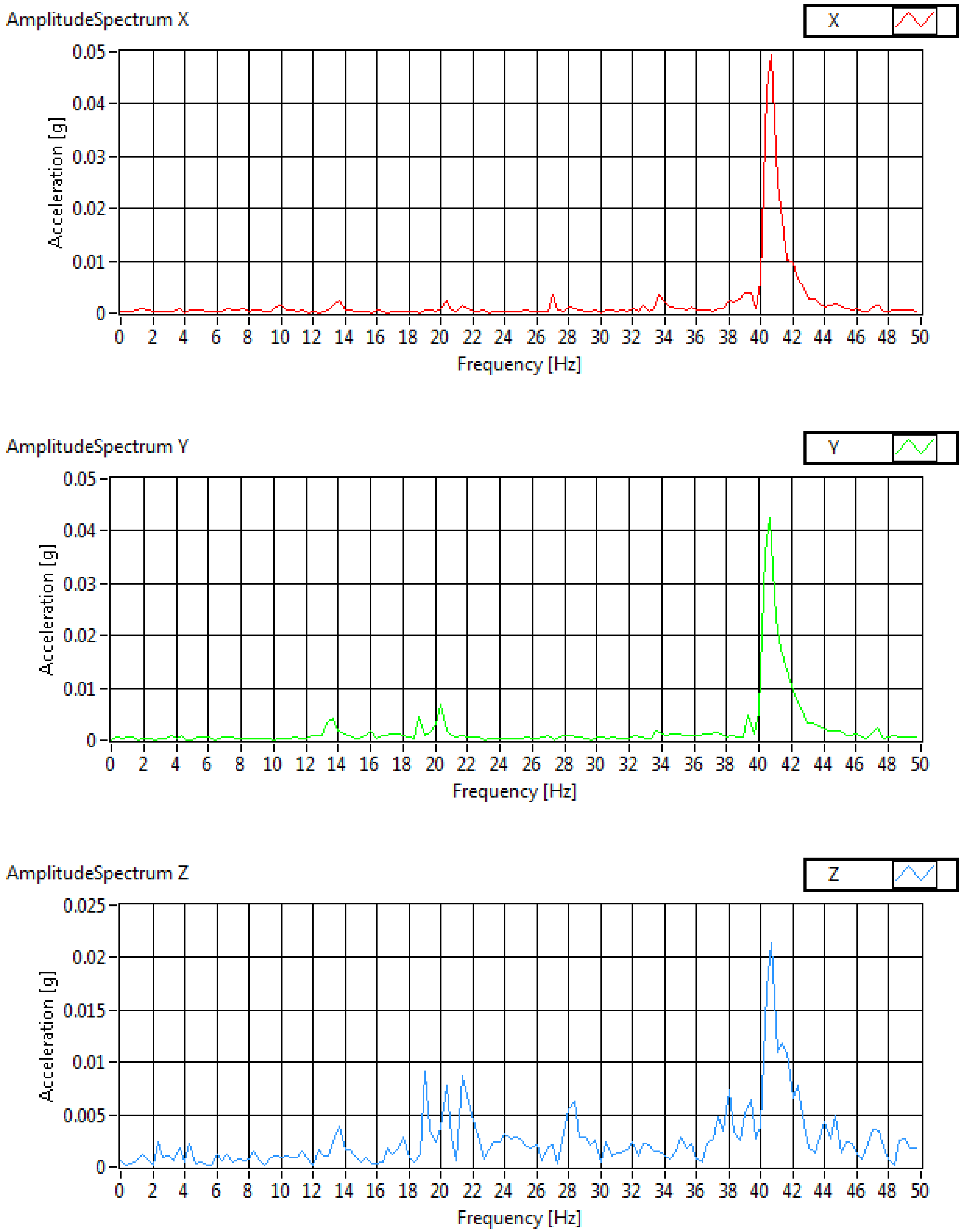


Figure 83 Sterling FD test 04, acceleration spectra (time 21-24)

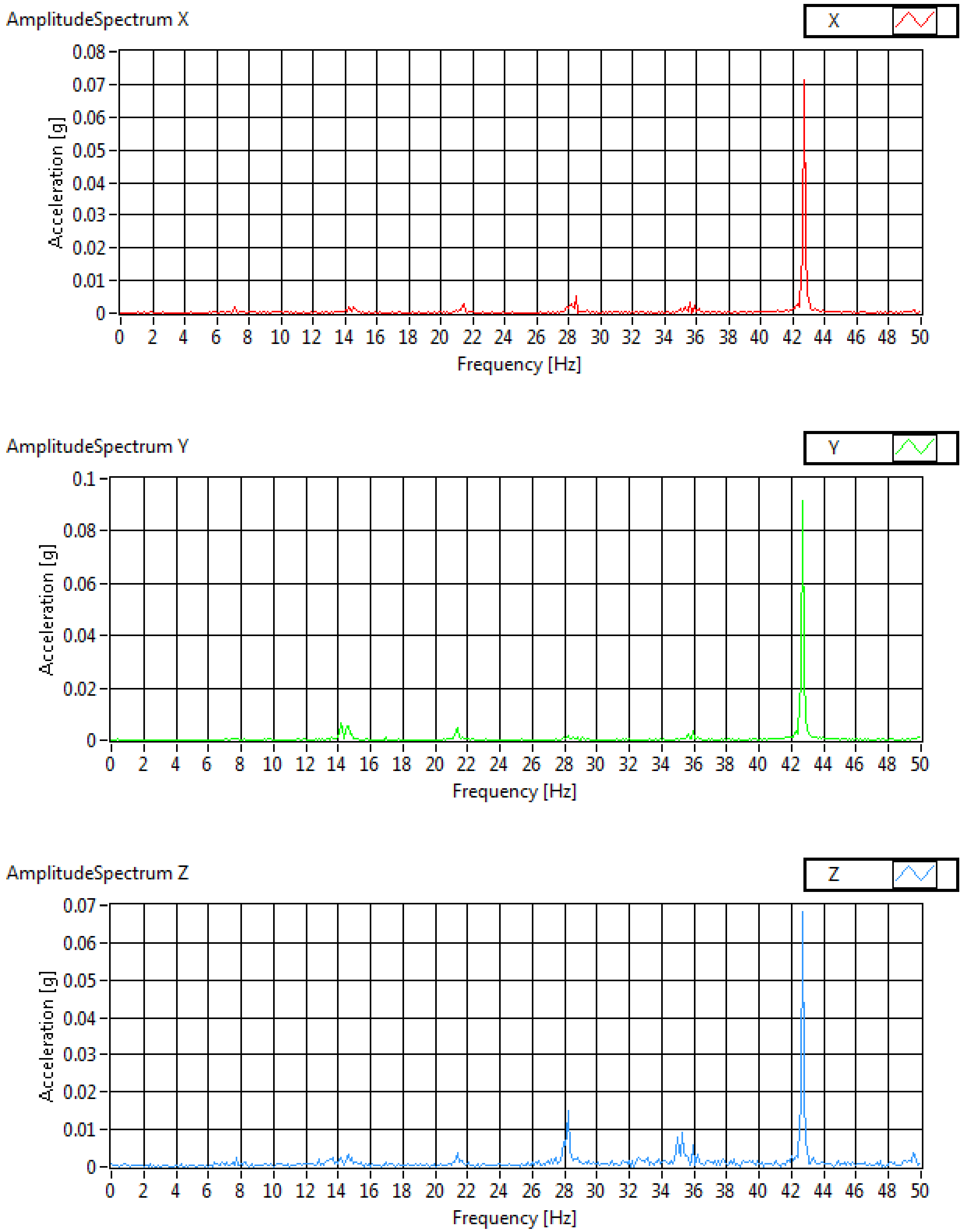


Figure 84 Sterling FD test 04, acceleration spectra (time 25-35)

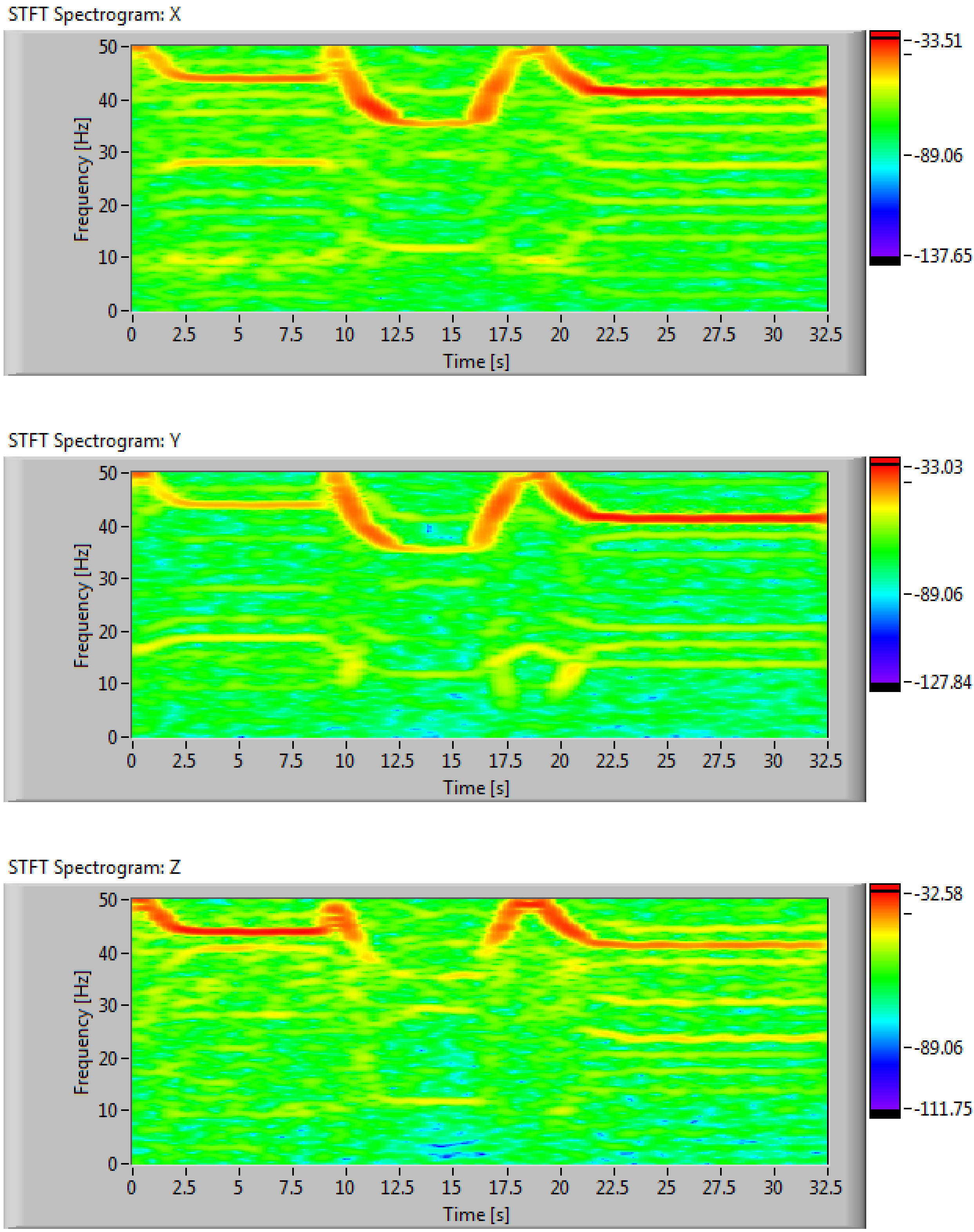


Figure 85 Sterling FD test 05, acceleration spectrogram

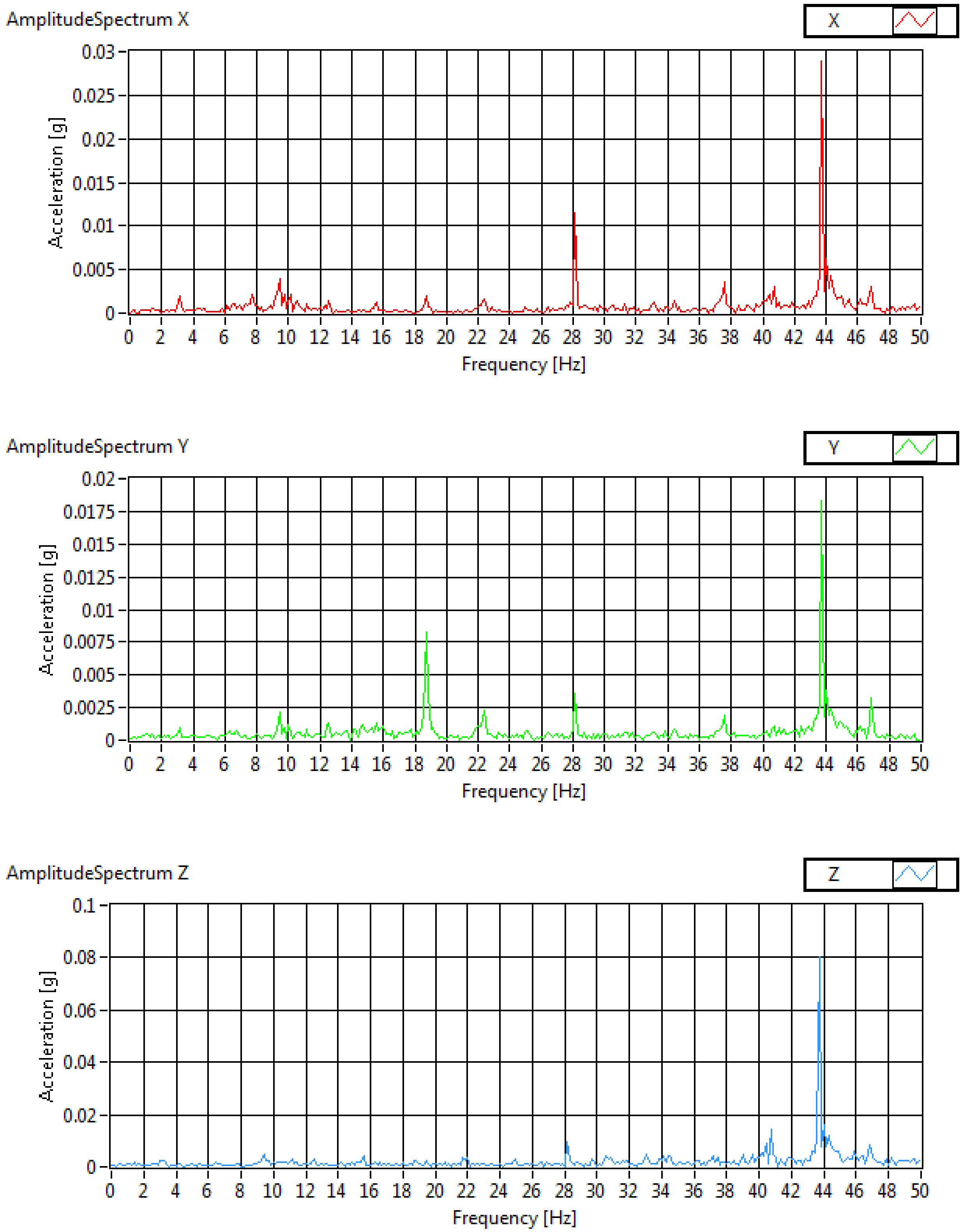
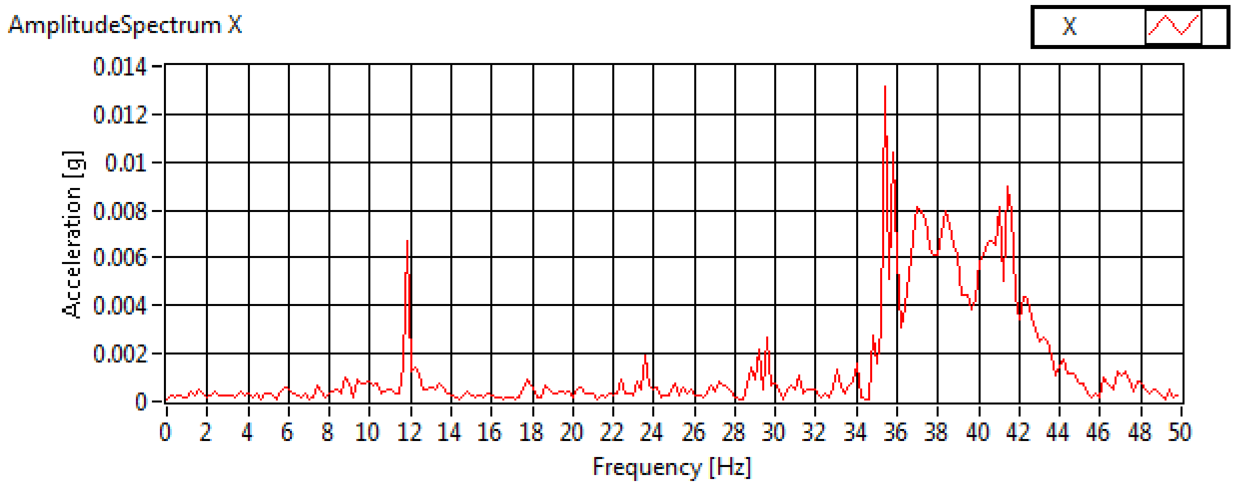
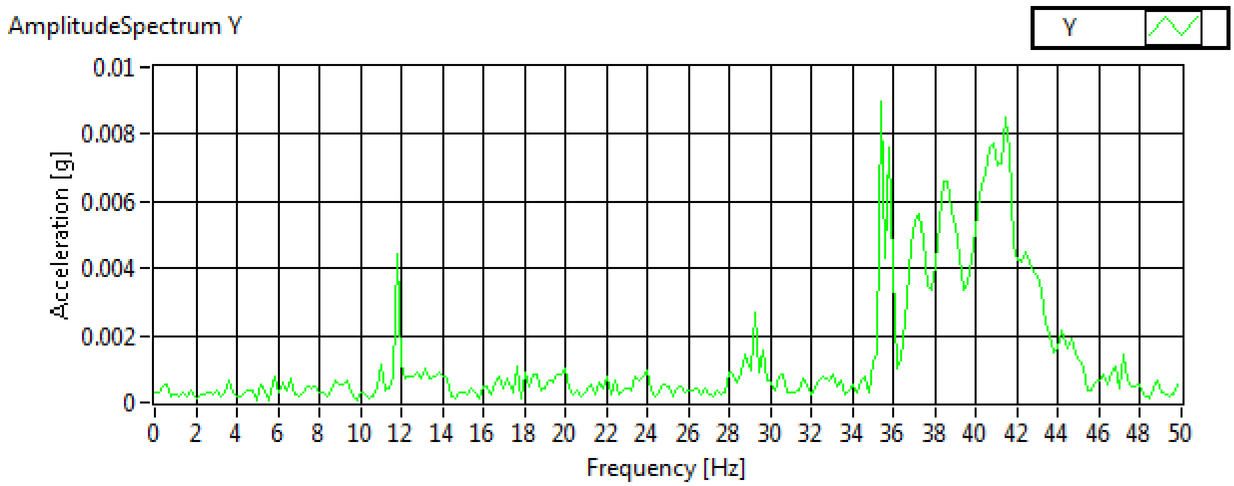


Figure 86 Sterling FD test 05, acceleration spectra (time 2-9)





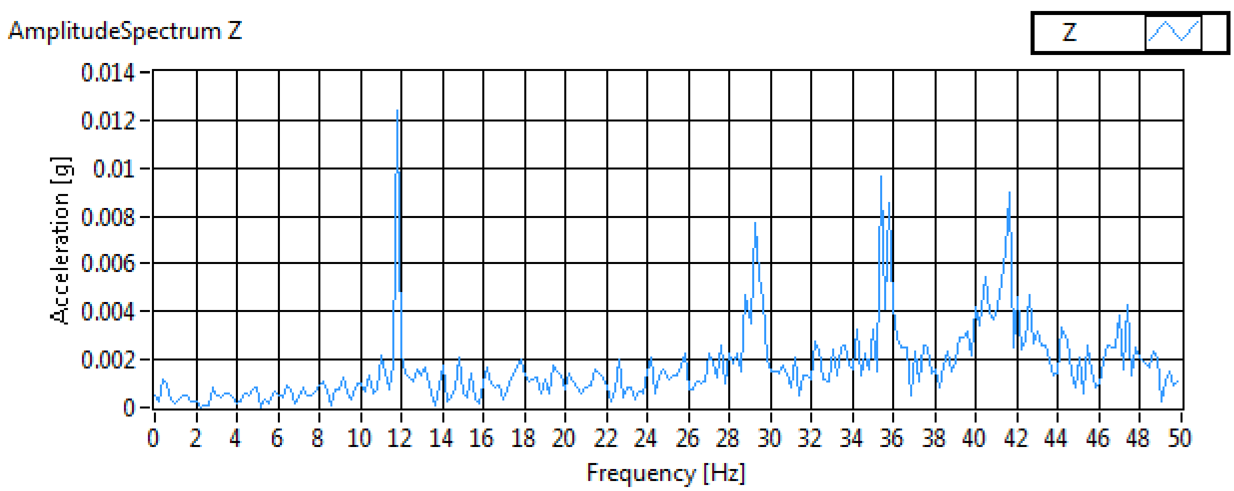
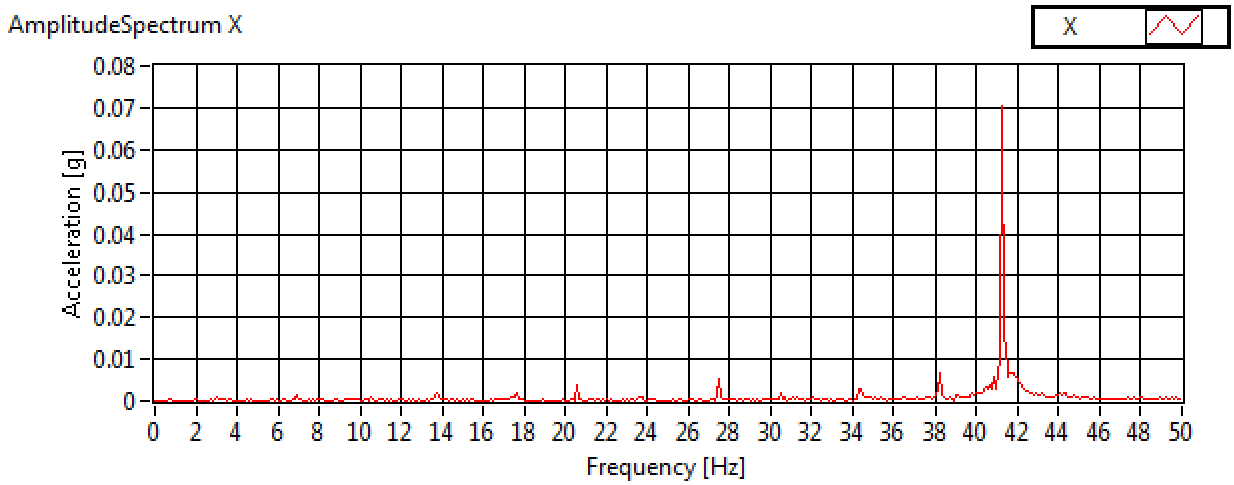
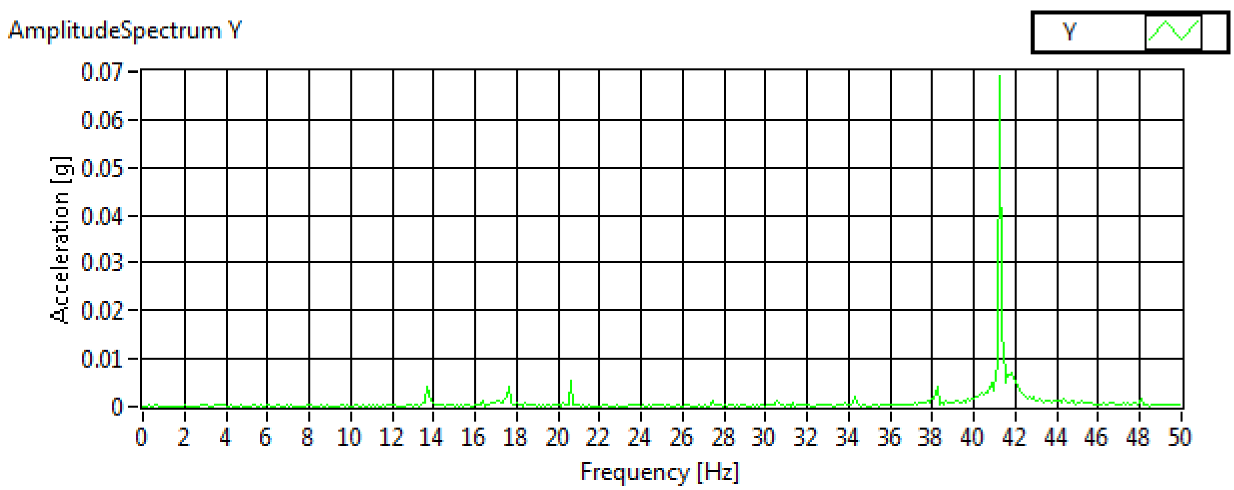


Figure 87 Sterling FD test 05, acceleration spectra (time 12-17)





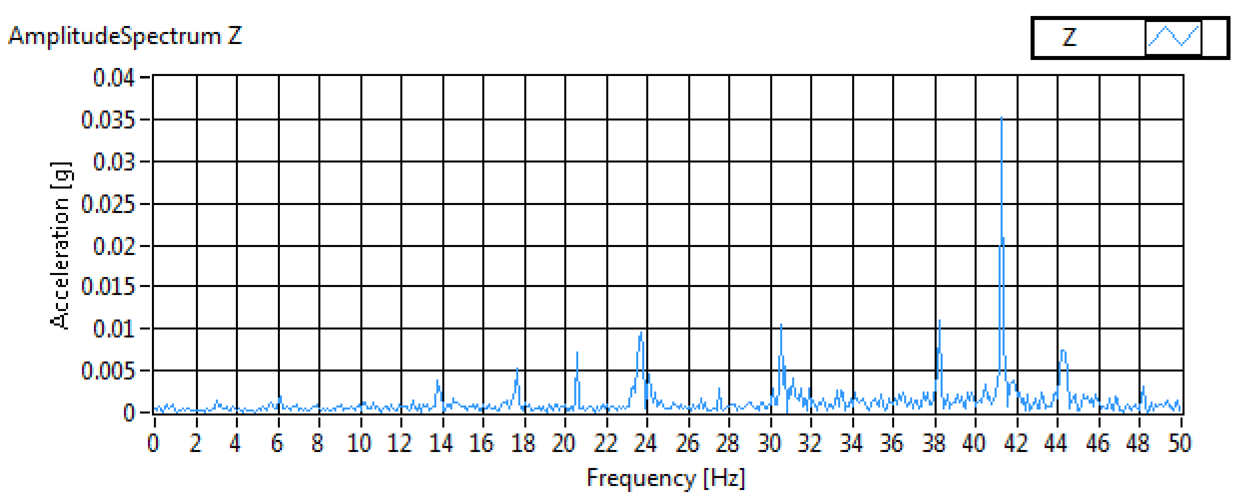


Figure 88 Sterling FD test 05, acceleration spectra (time 22-32)

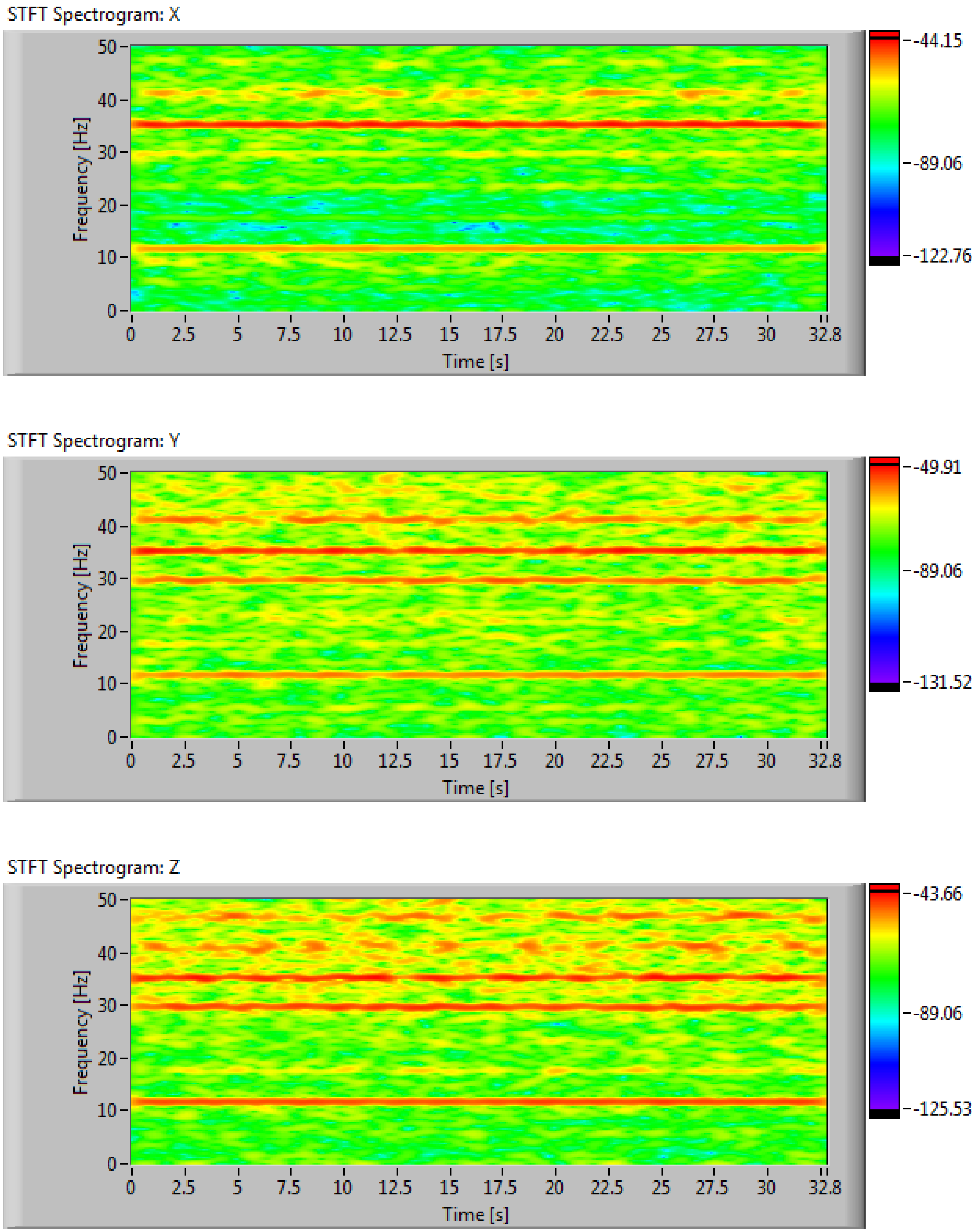


Figure 89 Sterling FD test 06, acceleration spectrogram

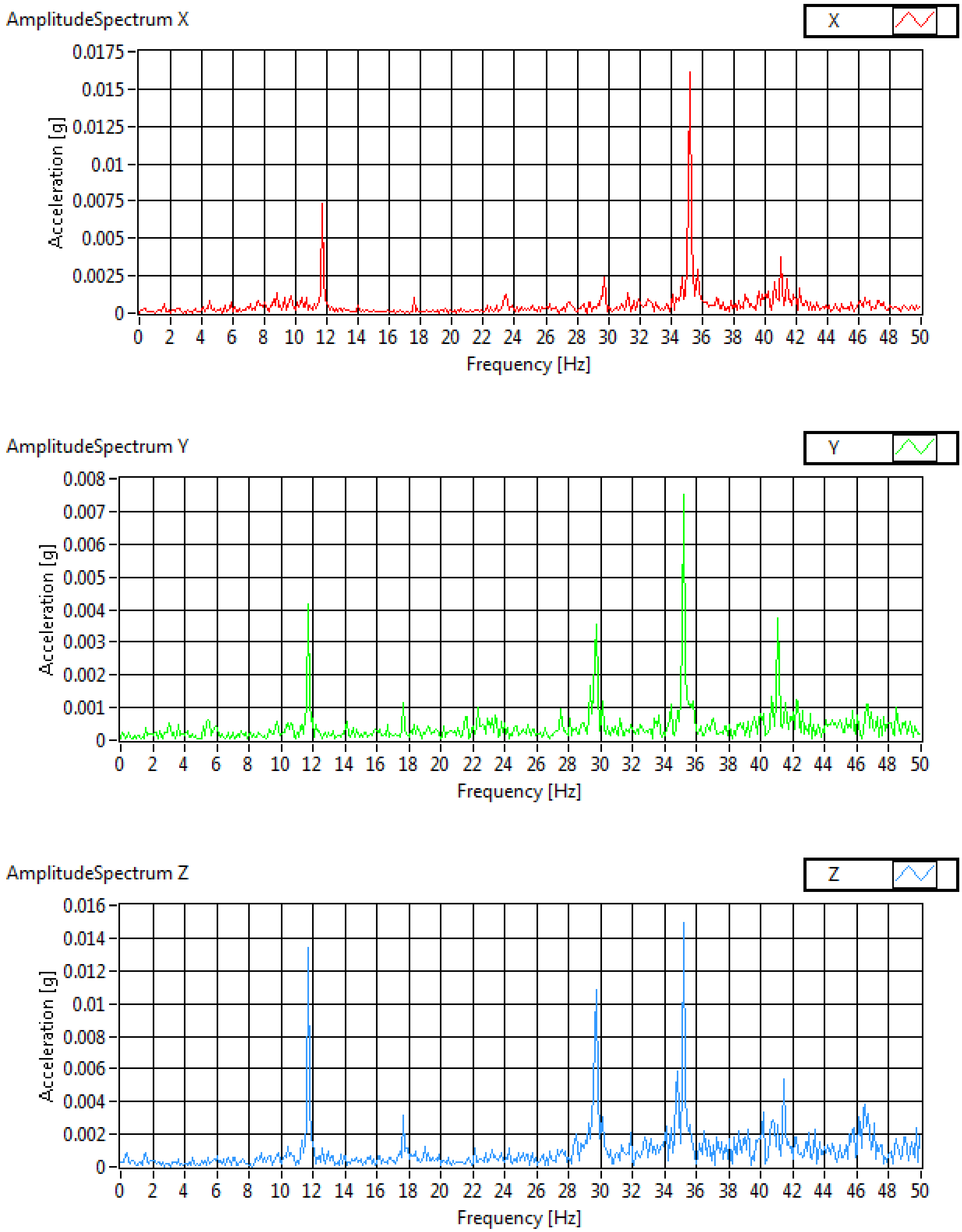


Figure 90 Sterling FD test 06, acceleration spectra

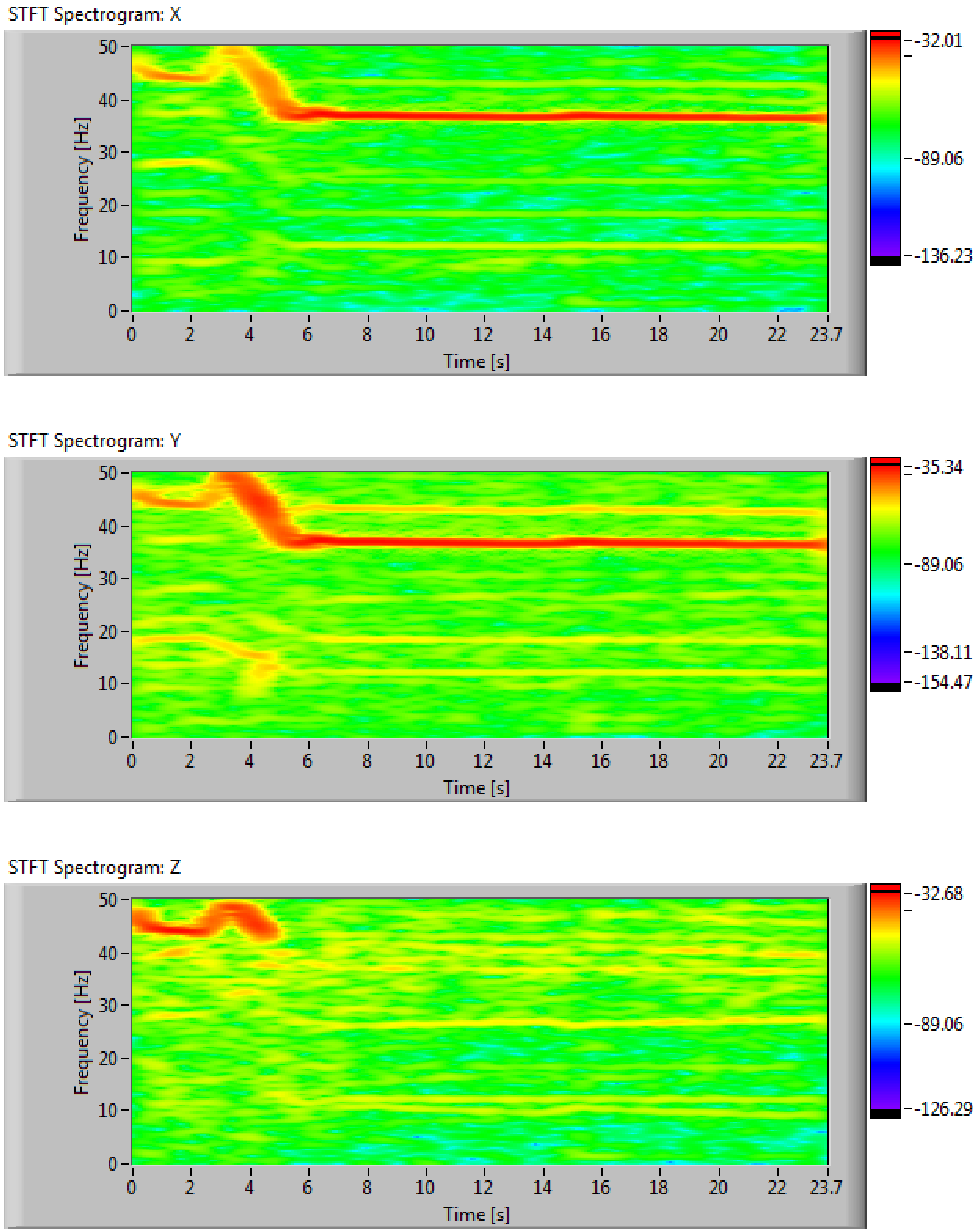


Figure 91 Sterling FD test 07, acceleration spectrogram

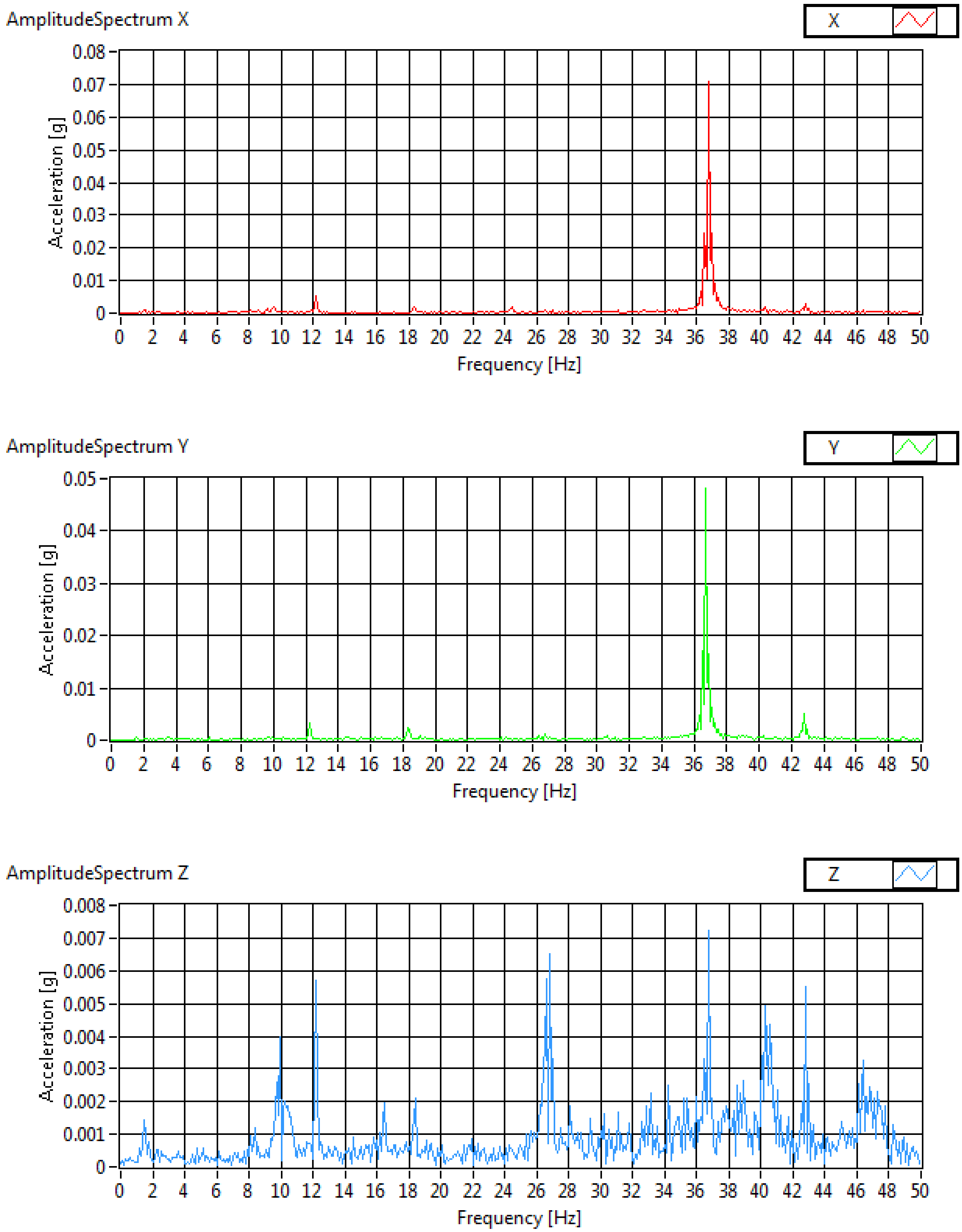


Figure 92 Sterling FD test 07, acceleration spectra (time 8-18)

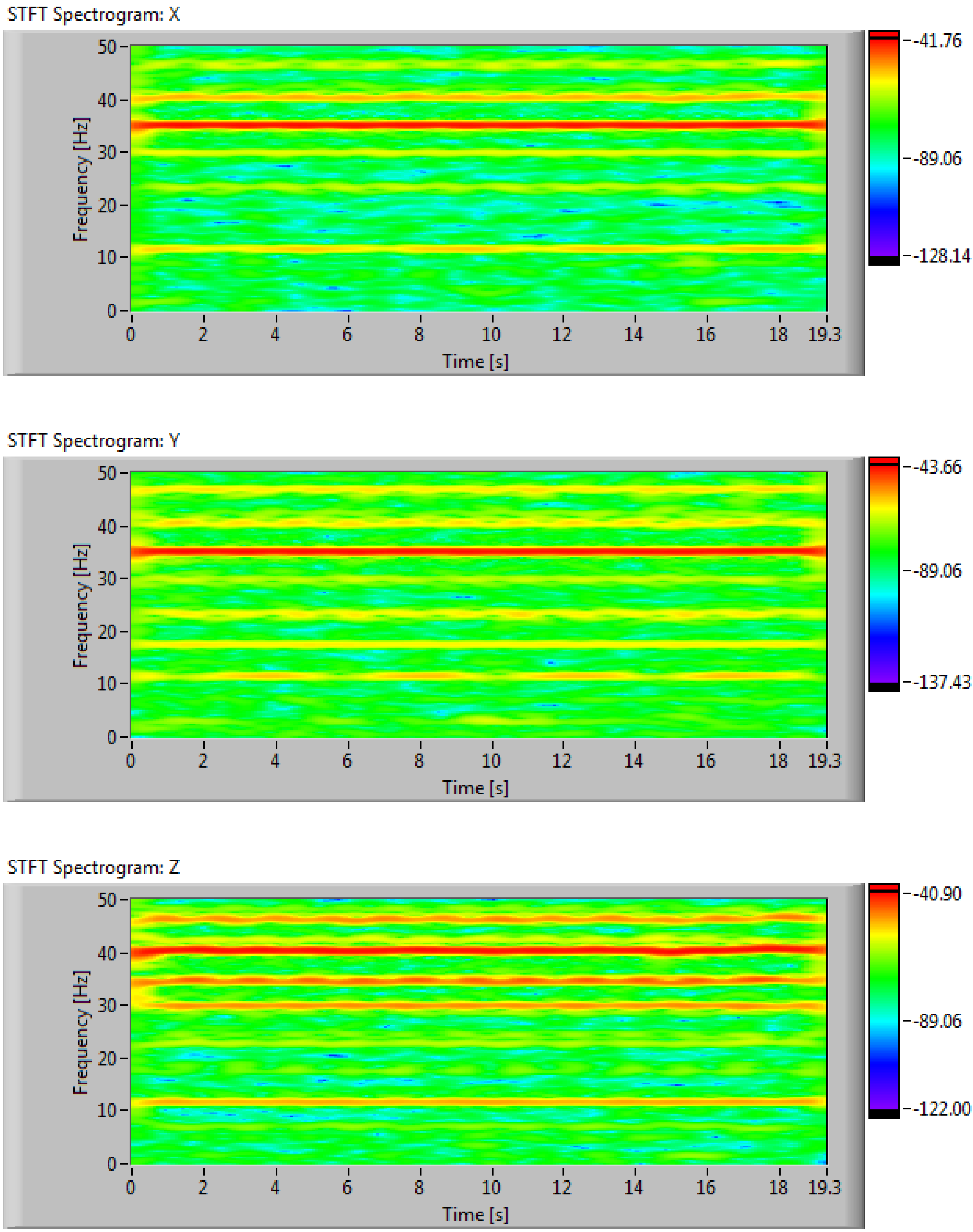


Figure 93 Sterling FD test 08, acceleration spectrogram

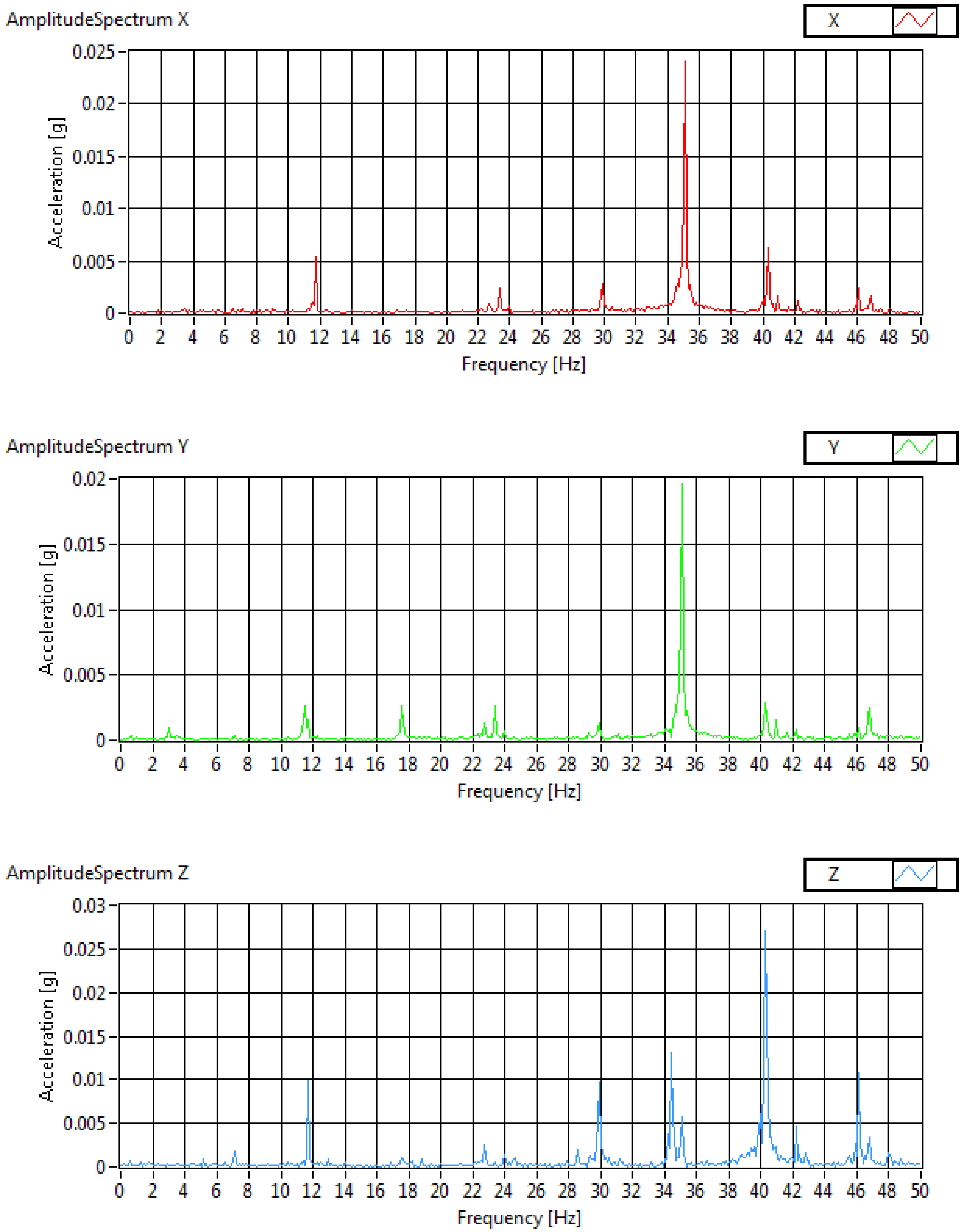


Figure 94 Sterling FD test 08, acceleration spectra

3.5.1.3 Engine 4 Type (d) Test

Table 28 Engine 4 type (d) test spectral peaks, x-axis

Test	First Peak, X		Second Peak, X		Third Peak, X		Fourth Peak, X	
No.	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]
09	35.0	0.00720	29.8	0.00150	29.2	0.00120	11.4	0.00080
09	34.2	0.00860	22.8	0.00460	17.2	0.00200	31.0	0.00100
10	34.8	0.00820	11.6	0.00180	20.2	0.00160	29.0	0.00160
10	33.4	0.01020	11.2	0.00220	24.0	0.00180	20.0	0.00160
11	36.4	0.00260	37.4	0.00180	24.2	0.00140	12.2	0.00110
11	18.4	0.00580	44.2	0.00330	43.6	0.00190	28.0	0.00180
11	20.0	0.00260	13.6	0.00240	40.2	0.00220	6.6	0.00090

Table 29 Engine 4 type (d) test spectral peaks, y-axis

Test	First Peak, Y		Second Peak, Y		Third Peak, Y		Fourth Peak, Y	
No.	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]
09	35.0	0.00560	11.4	0.00190	29.2	0.00060	17.4	0.00060
09	34.2	0.00570	11.6	0.00250	22.8	0.00240	28.4	0.00080
10	34.8	0.00550	11.6	0.00460	16.8	0.00080	23.2	0.00070
10	11.2	0.00710	33.4	0.00320	24.0	0.00150	22.0	0.00100
11	36.4	0.00330	37.4	0.00250	12.2	0.00160	25.2	0.00130
11	44.2	0.00340	18.4	0.00310	43.6	0.00170	4.4	0.00110
11	40.2	0.00660	20.0	0.00210	26.8	0.00130	13.4	0.00120

Table 30 Engine 4 type (d) test spectral peaks, z-axis

Test	First Peak, Z		Second Peak, Z		Third Peak, Z		Fourth Peak, Z	
No.	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]
09	35.0	0.00610	30.0	0.00190	11.4	0.00130	17.4	0.00110
09	34.2	0.00780	17.2	0.00360	11.6	0.00340	22.8	0.00200
10	34.8	0.00720	11.6	0.00690	5.8	0.00130	17.4	0.00120
10	11.2	0.00900	33.4	0.00880	5.6	0.00260	20.0	0.00160
11	36.4	0.00380	37.4	0.00250	12.2	0.00250	5.6	0.00160
11	44.2	0.00520	18.4	0.00470	28.0	0.00190	16.2	0.00160
11	40.2	0.00670	6.6	0.00180	20.0	0.00180	13.4	0.00130

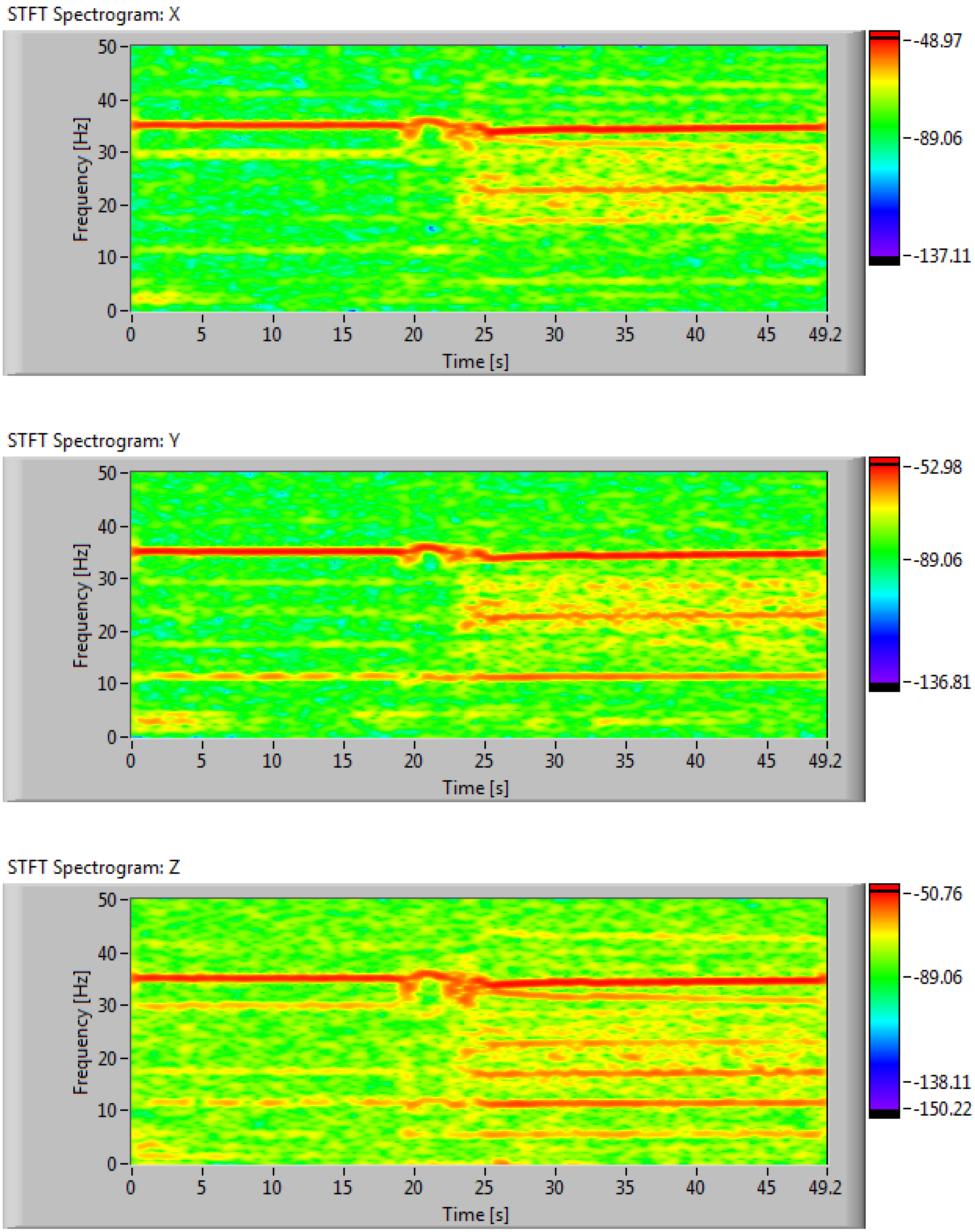
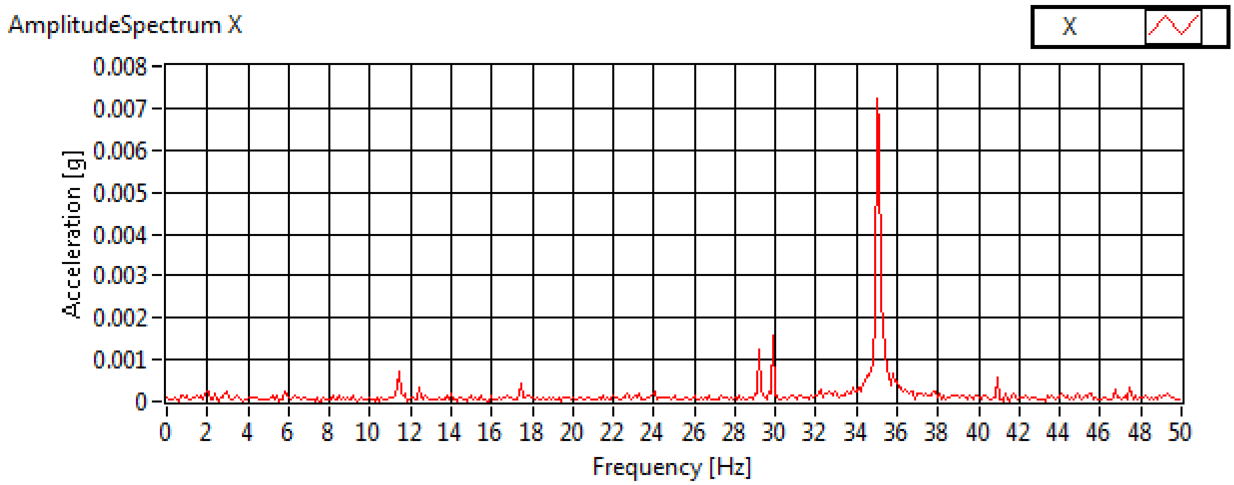
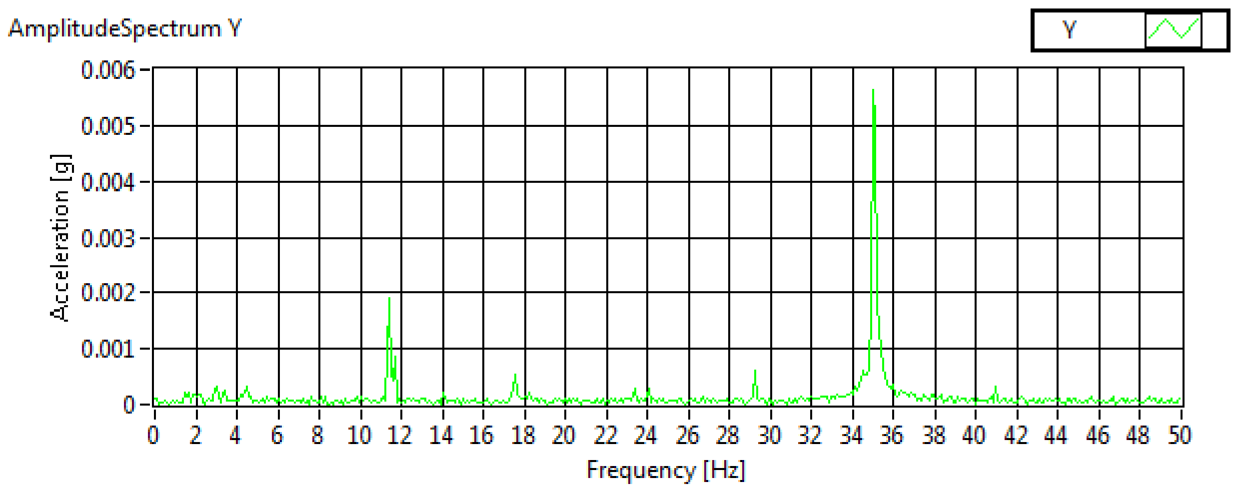


Figure 95 Sterling FD test 09, acceleration spectrogram





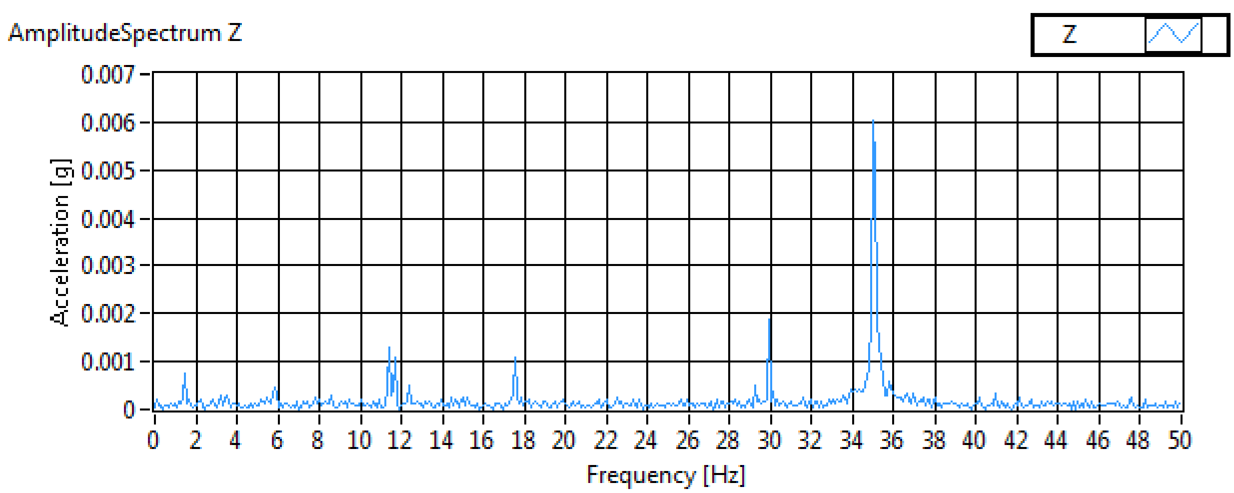


Figure 96 Sterling FD test 09, acceleration spectra (time 5-15)

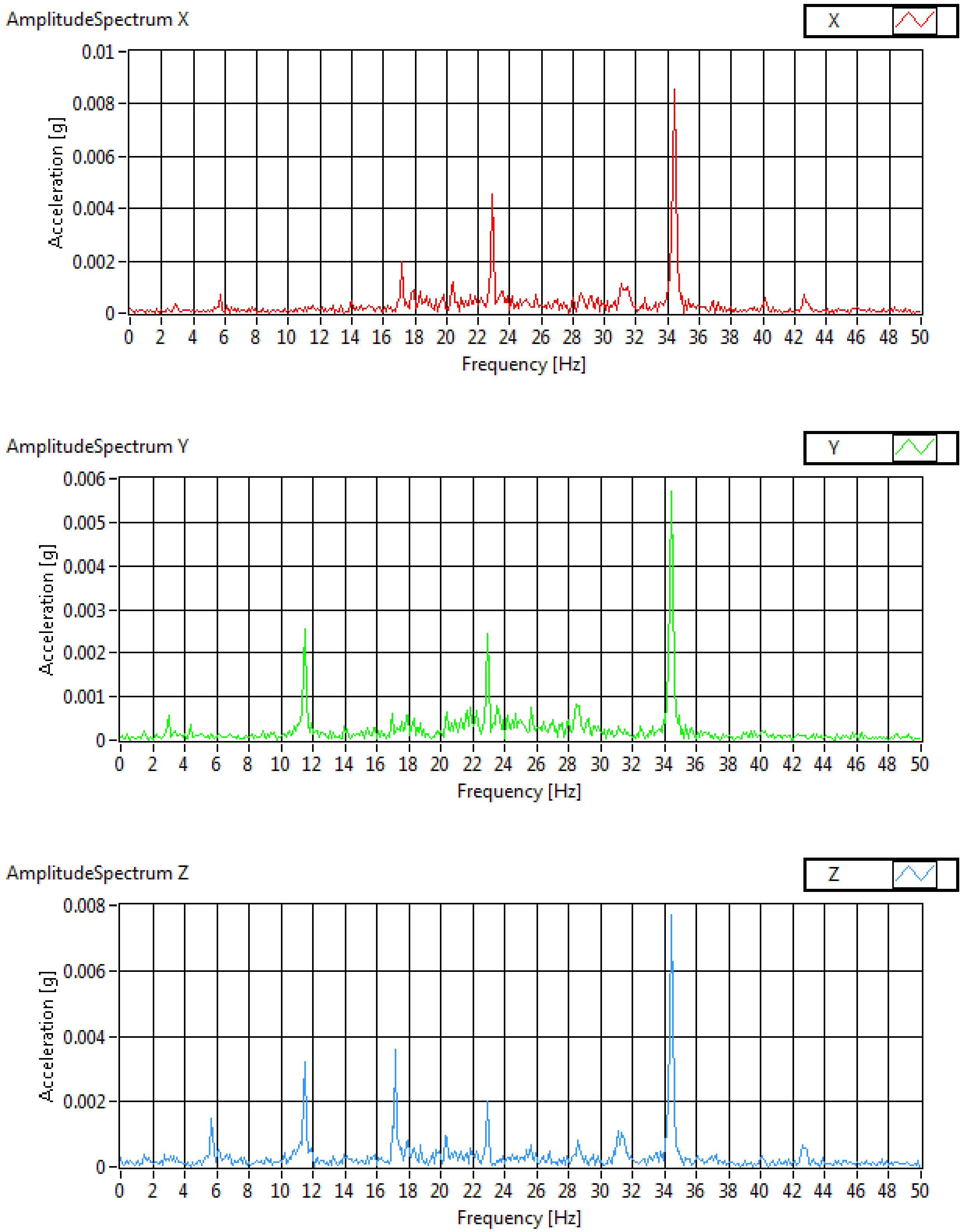


Figure 97 Sterling FD test 09, acceleration spectra (time 35-45)

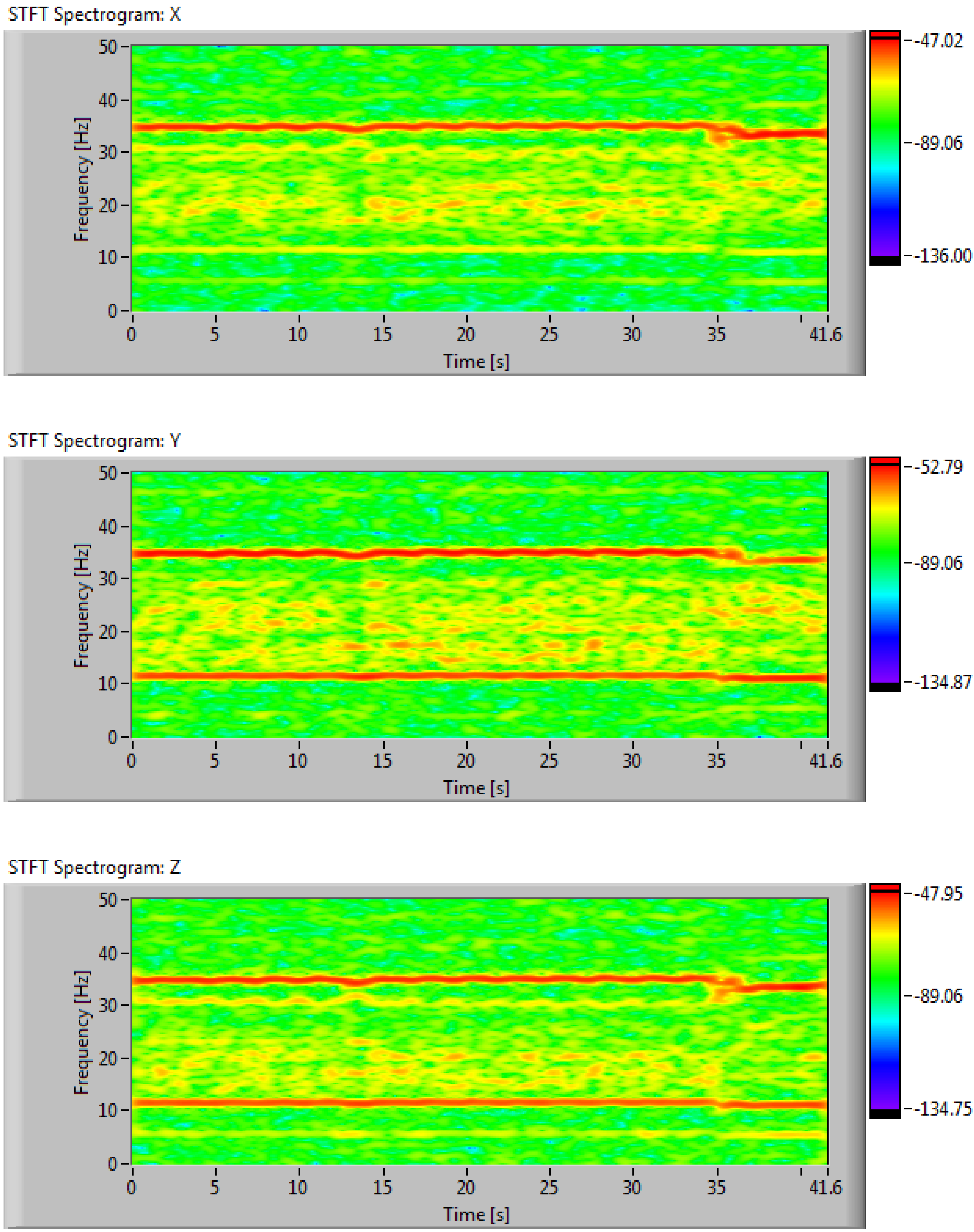


Figure 98 Sterling FD test 10, acceleration spectrogram

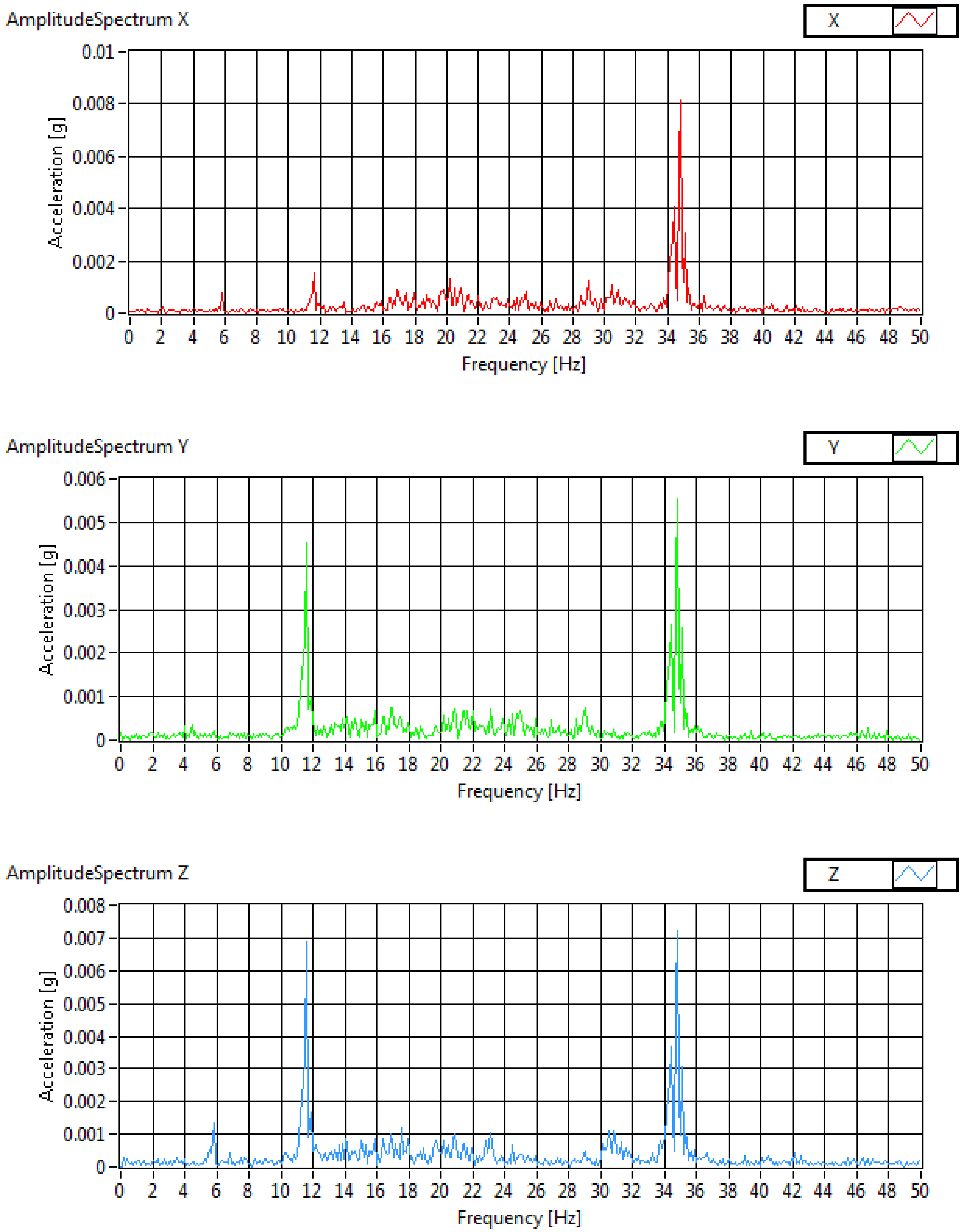


Figure 99 Sterling FD test 10, acceleration spectra (time 5-15)

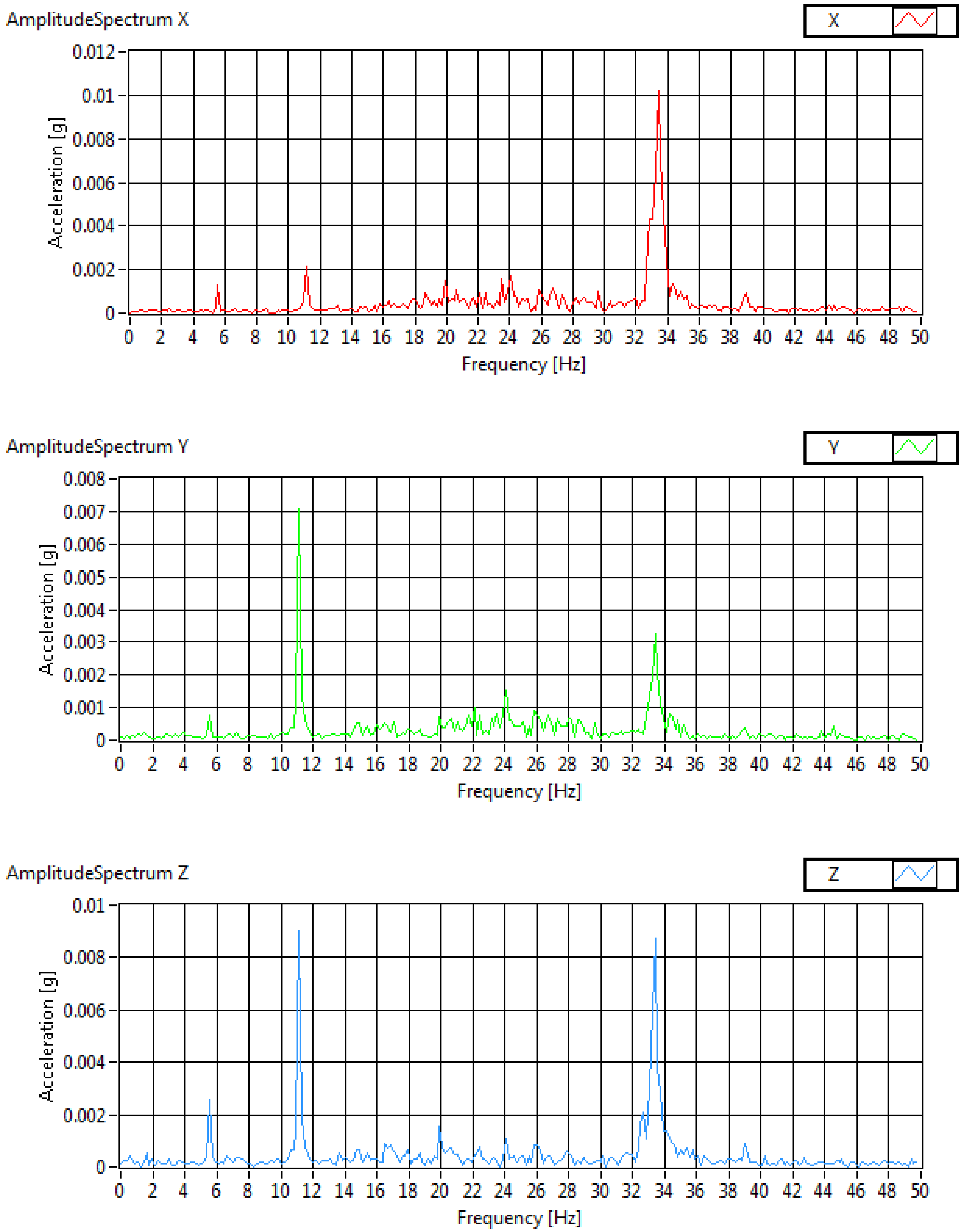


Figure 100 Sterling FD test 10, acceleration spectra (time 36-41.6)

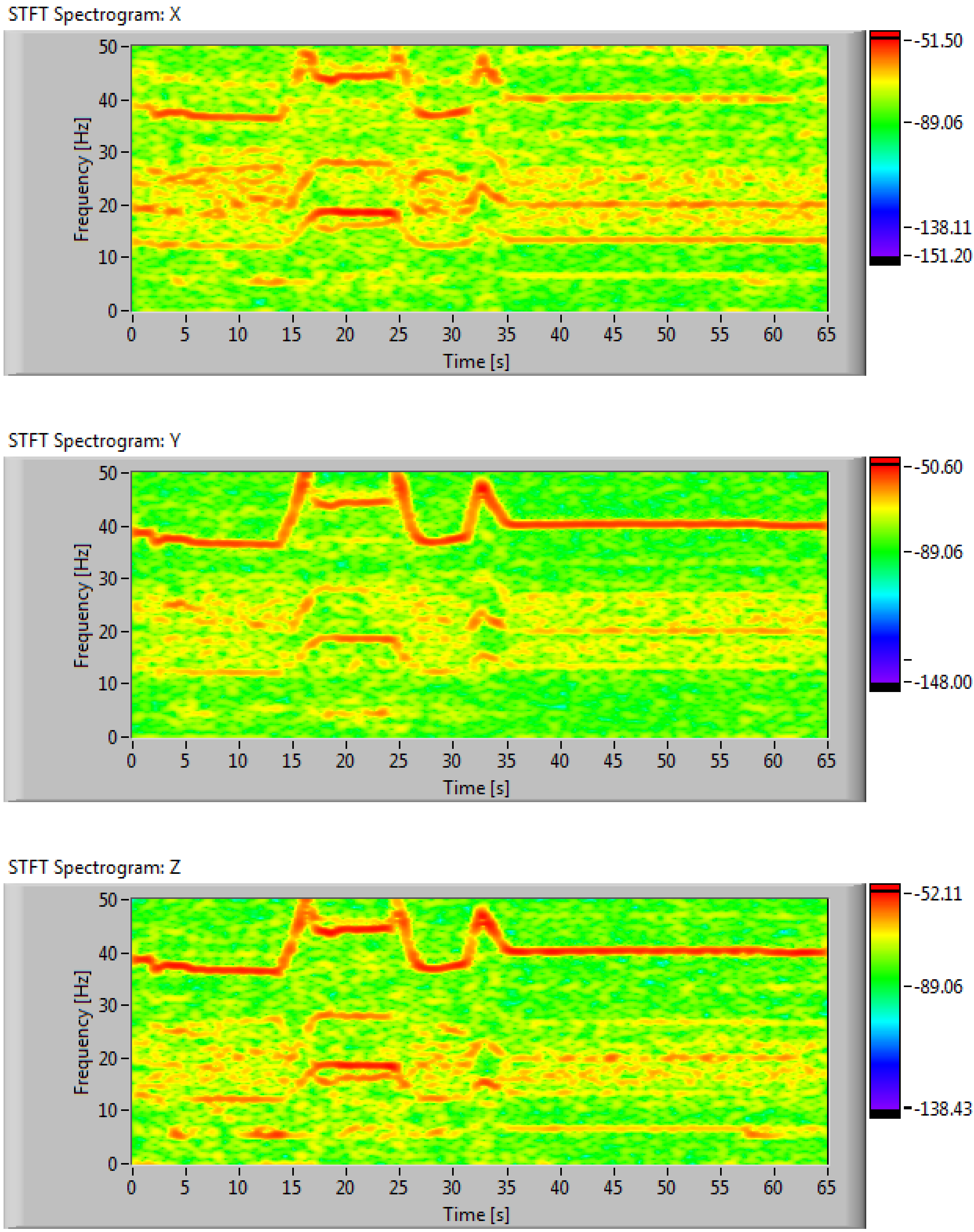


Figure 101 Sterling FD test 11, acceleration spectrogram

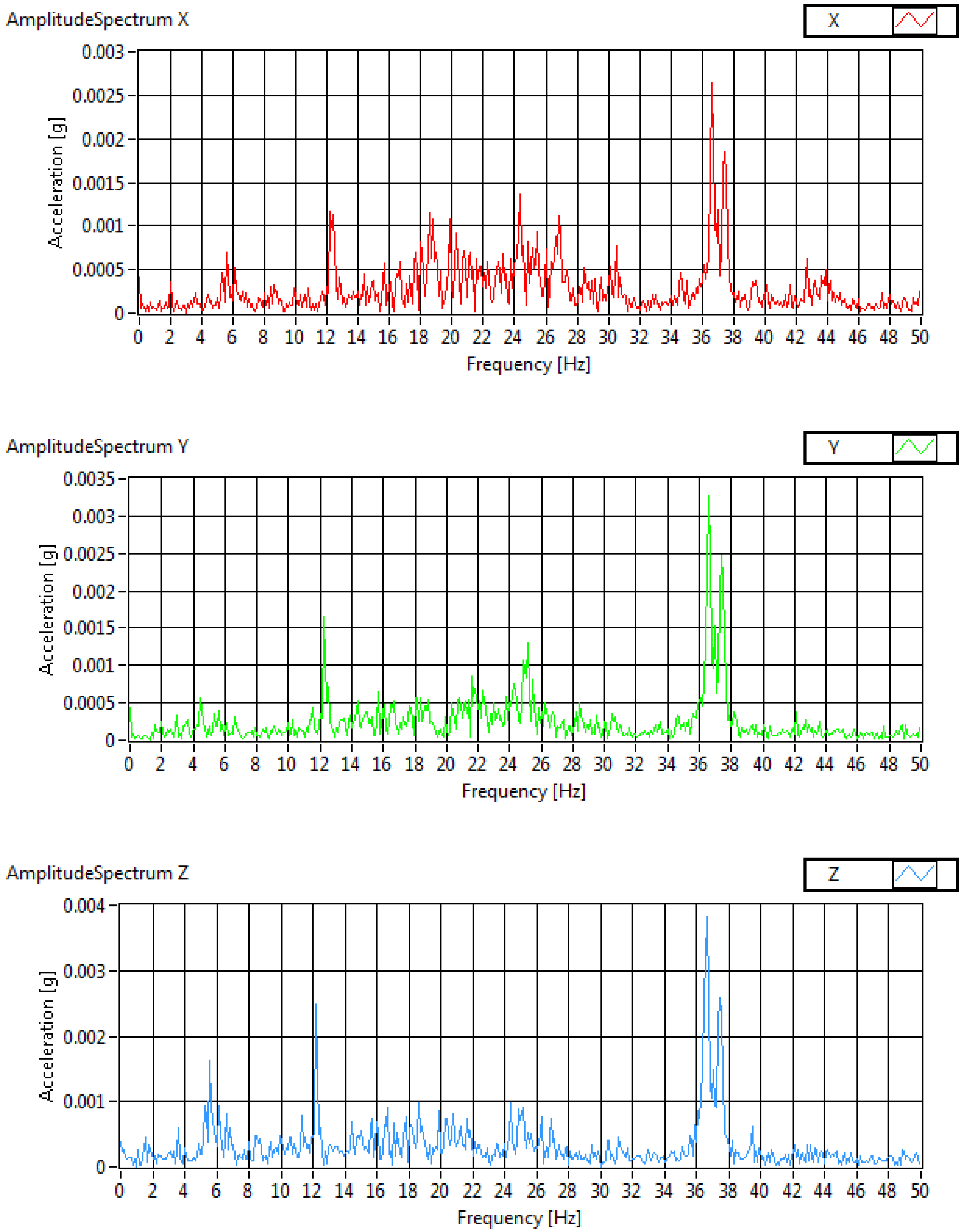


Figure 102 Sterling FD test 11, acceleration spectra (time 2-12)

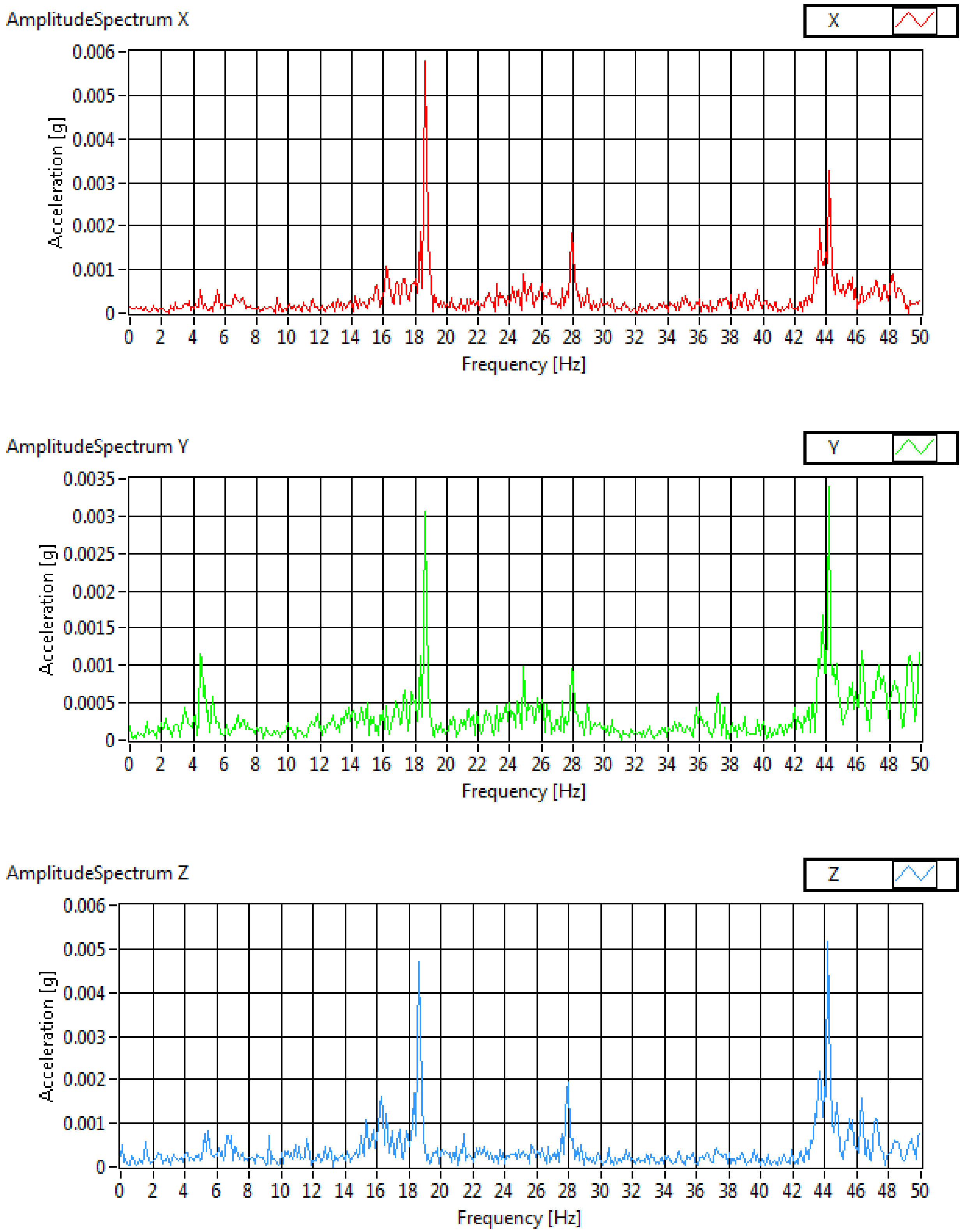


Figure 103 Sterling FD test 11, acceleration spectra (time 15-25)

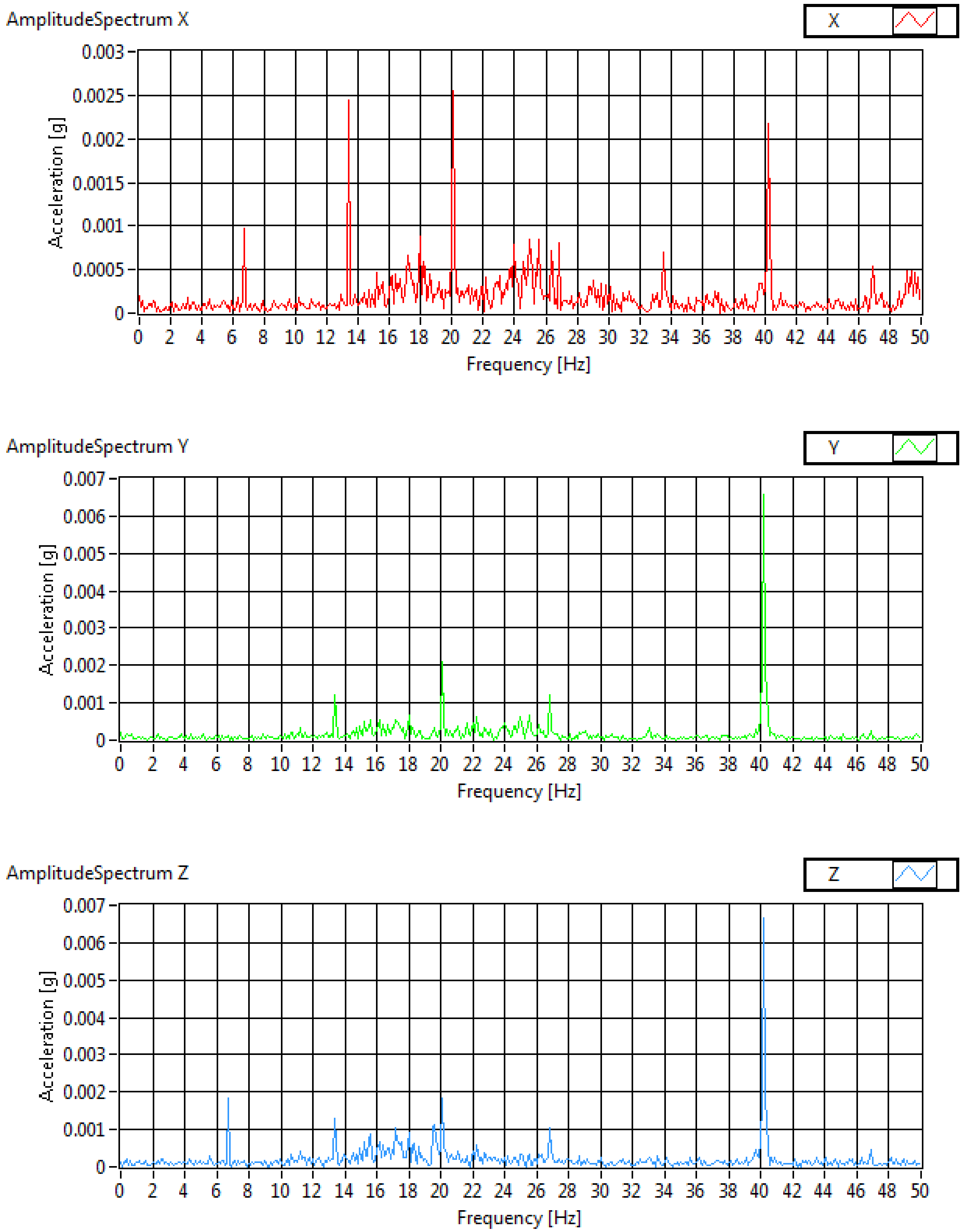


Figure 104 Sterling FD test 11, acceleration spectra (time 40-50)

3.5.1.4 Engine 2 Type (a) Test

Table 31 Engine 2 type (a) test spectral peaks, x-axis

Test No.	First Peak, X [Hz]	First Peak, X [g]	Second Peak, X [Hz]	Second Peak, X [g]	Third Peak, X [Hz]	Third Peak, X [g]	Fourth Peak, X [Hz]	Fourth Peak, X [g]
12	30.4	0.01760	45.6	0.00320	29.8	0.00280	40.8	0.00200
13	30.4	0.01850	29.8	0.00350	45.6	0.00300	40.8	0.00200

Table 32 Engine 2 type (a) test spectral peaks, y-axis

Test No.	First Peak, Y [Hz]	First Peak, Y [g]	Second Peak, Y [Hz]	Second Peak, Y [g]	Third Peak, Y [Hz]	Third Peak, Y [g]	Fourth Peak, Y [Hz]	Fourth Peak, Y [g]
12	30.4	0.01060	29.8	0.00460	45.6	0.00280	3.0	0.00140
13	30.4	0.01600	29.8	0.00380	45.6	0.00300	39.2	0.00140

Table 33 Engine 2 type (a) test spectral peaks, z-axis

Test No.	First Peak, Z [Hz]	First Peak, Z [g]	Second Peak, Z [Hz]	Second Peak, Z [g]	Third Peak, Z [Hz]	Third Peak, Z [g]	Fourth Peak, Z [Hz]	Fourth Peak, Z [g]
12	30.4	0.01020	29.8	0.00360	45.6	0.00180	3.0	0.00120
13	30.4	0.01200	29.8	0.00300	45.6	0.00180	36.4	0.00140

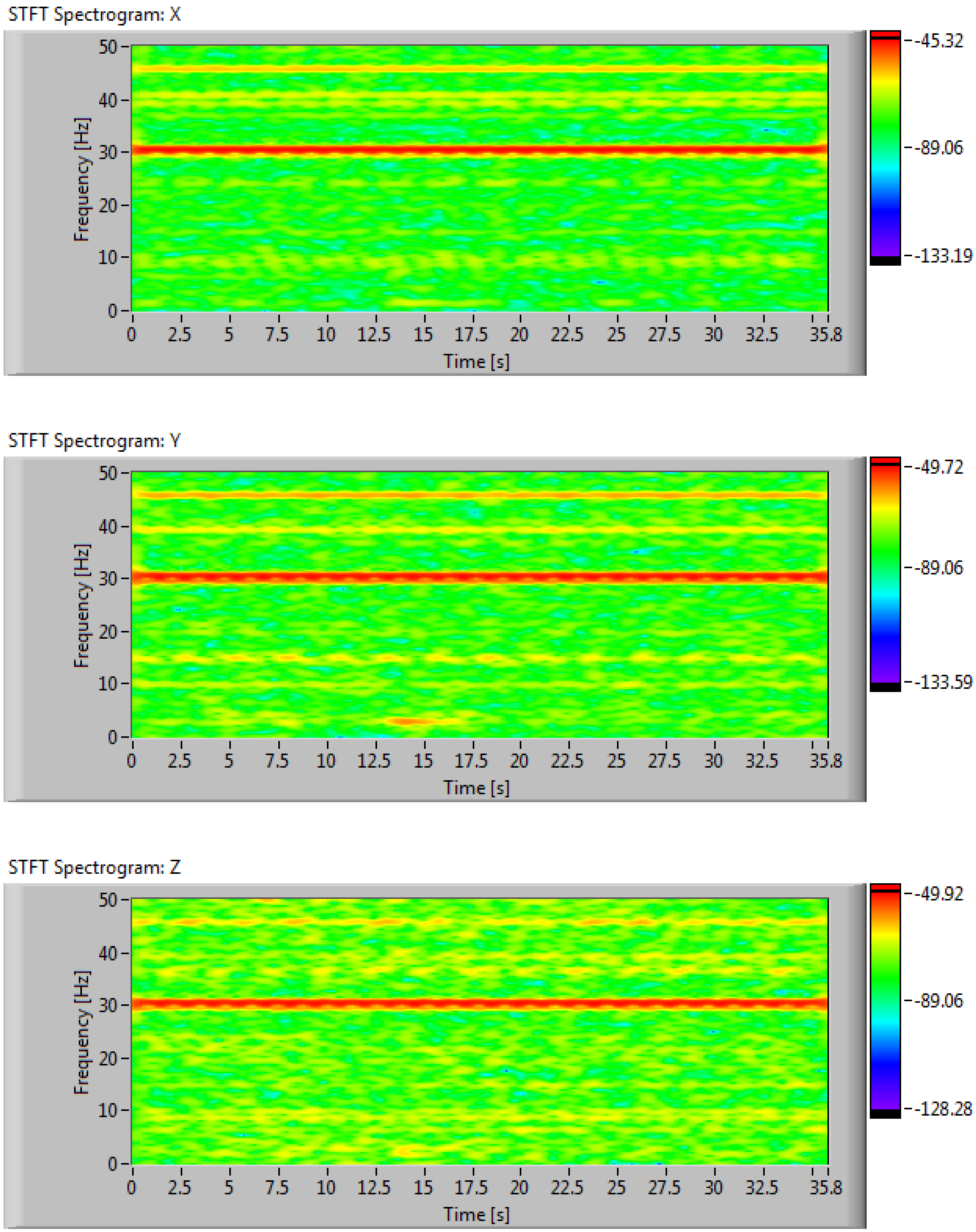


Figure 105 Sterling FD test 12, acceleration spectrogram

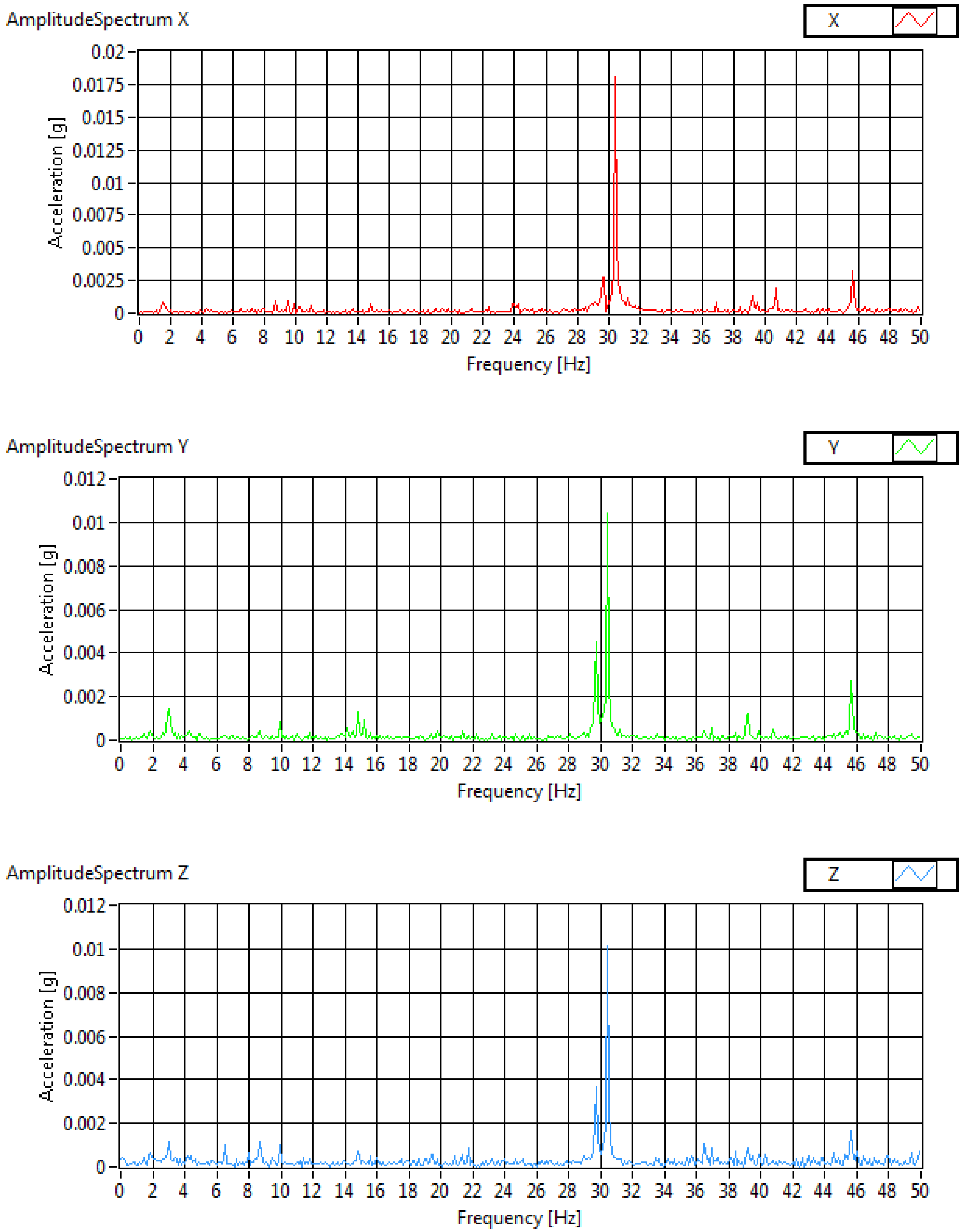


Figure 106 Sterling FD test 12, acceleration spectra

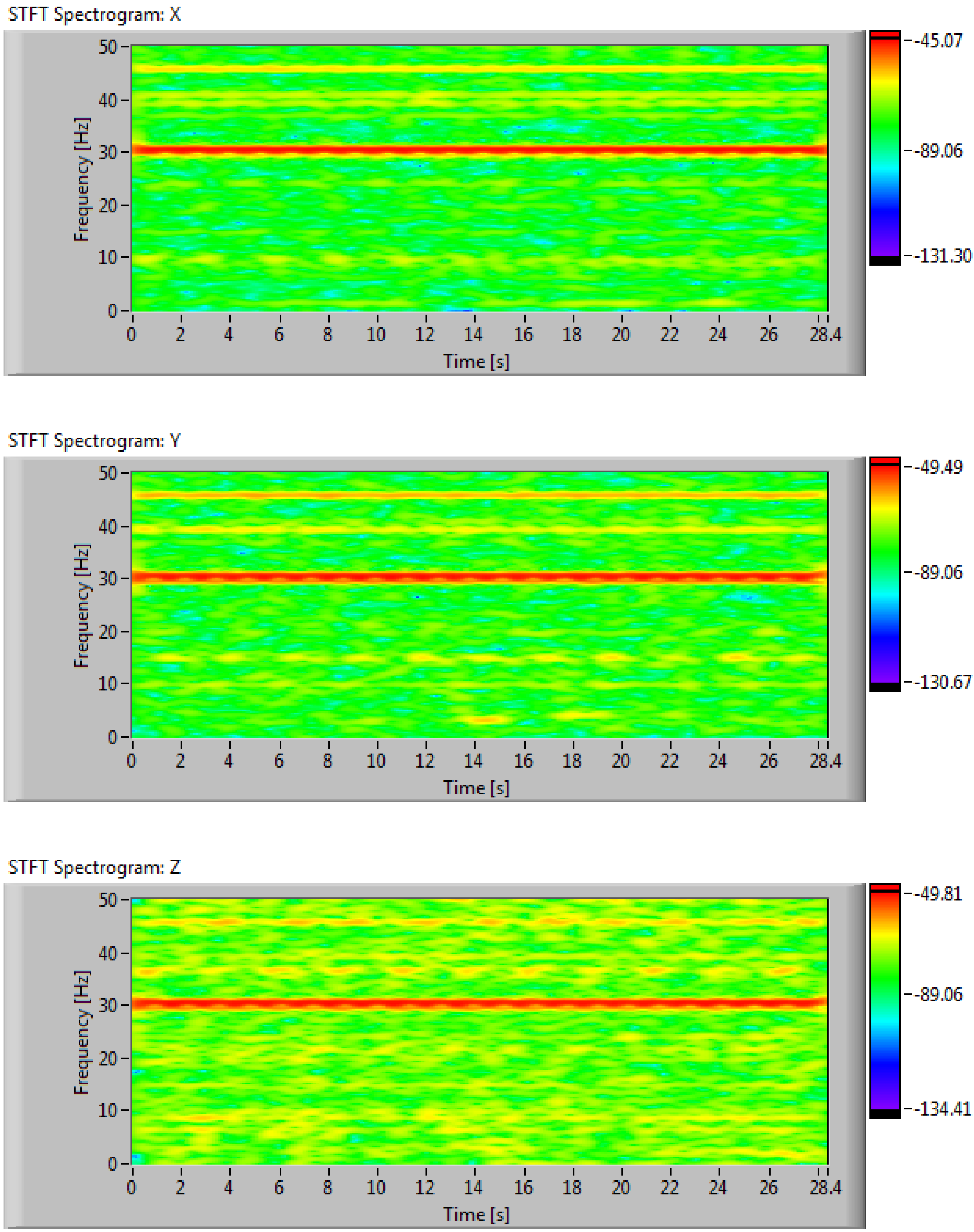


Figure 107 Sterling FD test 13, acceleration spectrogram

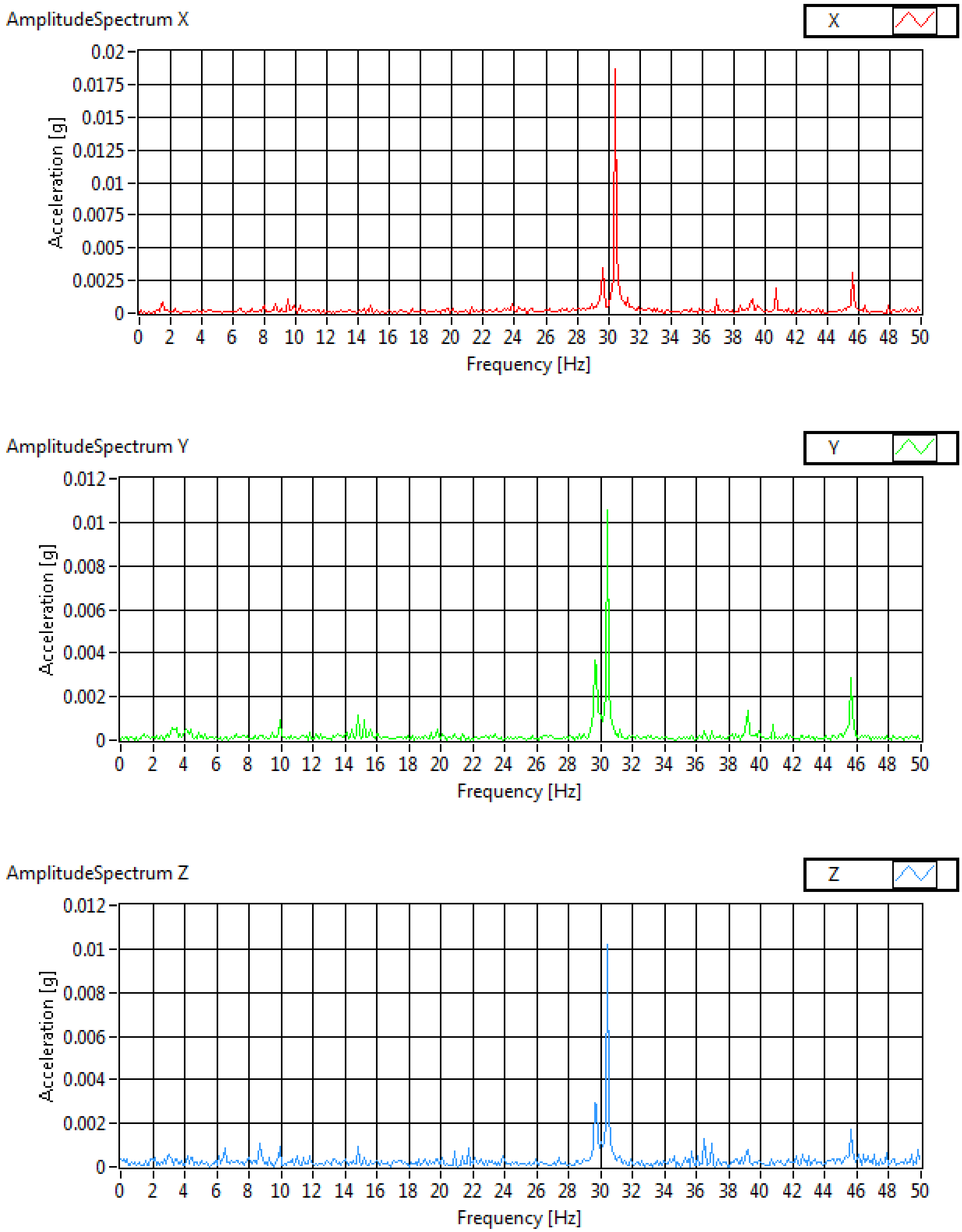


Figure 108 Sterling FD test 13, acceleration spectra

3.5.1.5 Engine 2 Type (c) Test

Table 34 Engine 2 type (c) test spectral peaks, x-axis

Test	First Peak, X		Second Peak, X		Third Peak, X		Fourth Peak, X	
No.	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]
14	45.6	0.03200	30.4	0.02600	8.8	0.01600	39.2	0.00900
15	45.6	0.03100	30.4	0.02400	8.8	0.01400	39.2	0.00750
16	45.6	0.03400	30.4	0.02450	8.8	0.01750	41.8	0.01000
18	30.2	0.03300	10.0	0.01350	9.4	0.00500	45.6	0.00400
19	29.8	0.03050	10.0	0.00950	19.2	0.00500	10.6	0.00500

Table 35 Engine 2 type (c) test spectral peaks, y-axis

Test	First Peak, Y		Second Peak, Y		Third Peak, Y		Fourth Peak, Y	
No.	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]
14	30.4	0.06500	45.6	0.02400	29.6	0.01300	36.8	0.00500
15	30.4	0.06300	45.6	0.02300	29.6	0.01000	39.2	0.00500
16	30.4	0.05900	45.6	0.02300	36.8	0.00600	8.8	0.00500
18	30.2	0.03800	10.0	0.02800	45.6	0.00700	20.8	0.00300
19	29.8	0.02850	10.0	0.01400	30.4	0.00800	45.6	0.00700

Table 36 Engine 2 type (c) test spectral peaks, z-axis

Test	First Peak, Z		Second Peak, Z		Third Peak, Z		Fourth Peak, Z	
No.	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]
14	30.4	0.07300	29.6	0.01100	45.6	0.00800	39.2	0.00700
15	30.4	0.07200	39.2	0.00800	45.6	0.00800	29.8	0.00800
16	30.4	0.07000	45.6	0.00900	39.2	0.00700	21.4	0.00400
18	10.0	0.06200	30.2	0.00900	45.6	0.00800	15.2	0.00300
19	10.0	0.03600	29.8	0.01050	45.6	0.00800	39.6	0.00250

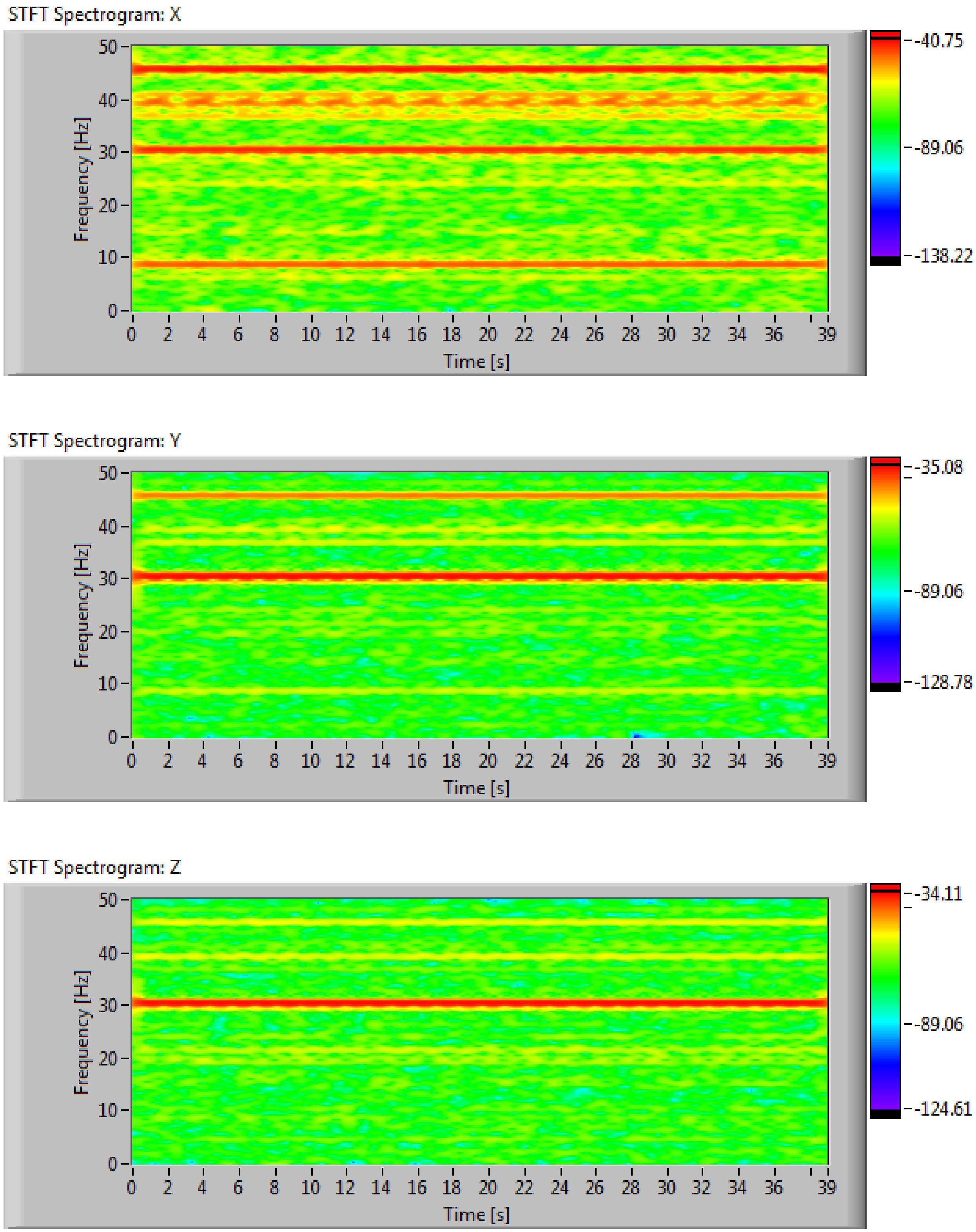


Figure 109 Sterling FD test 14, acceleration spectrogram

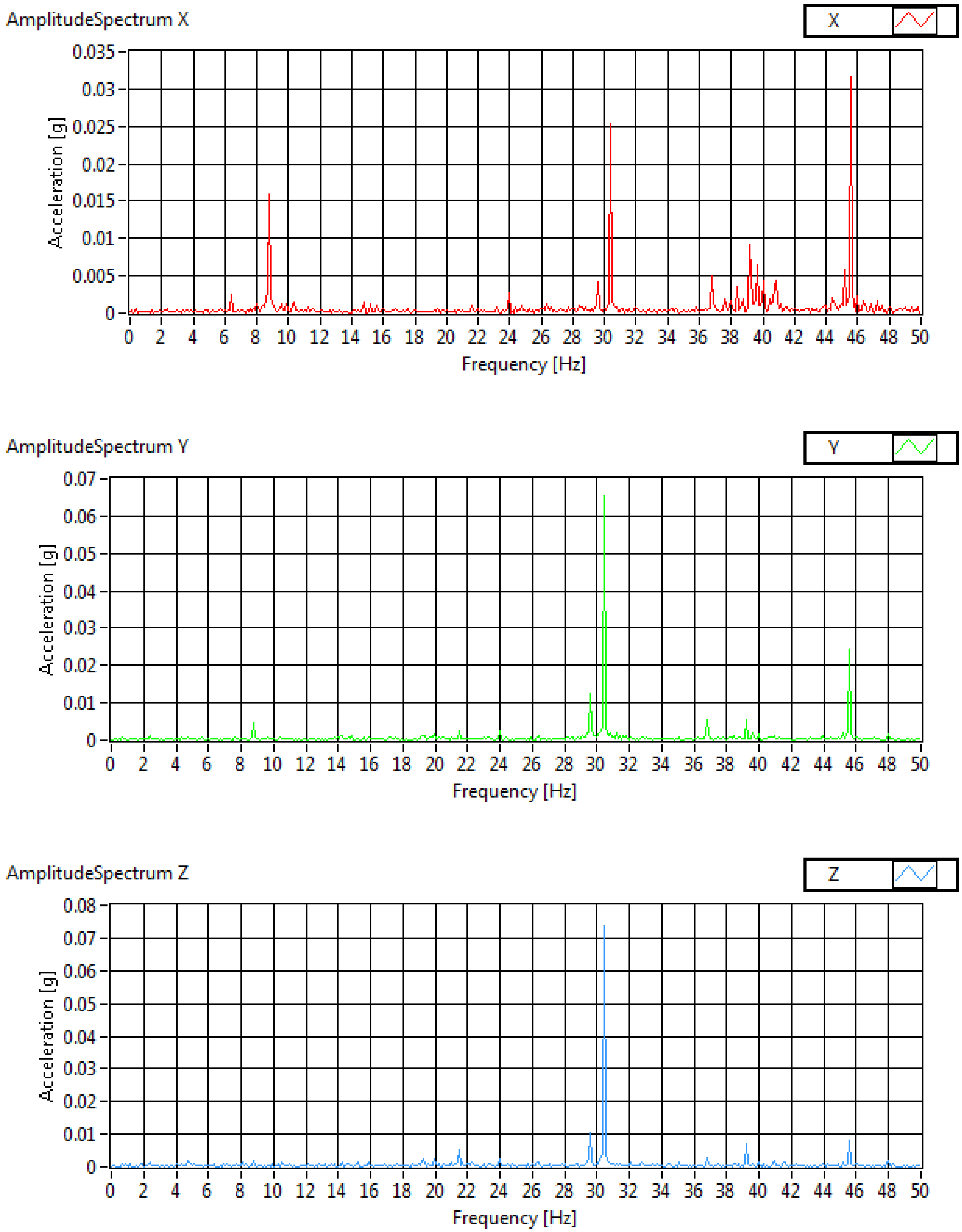


Figure 110 Sterling FD test 14, acceleration spectra

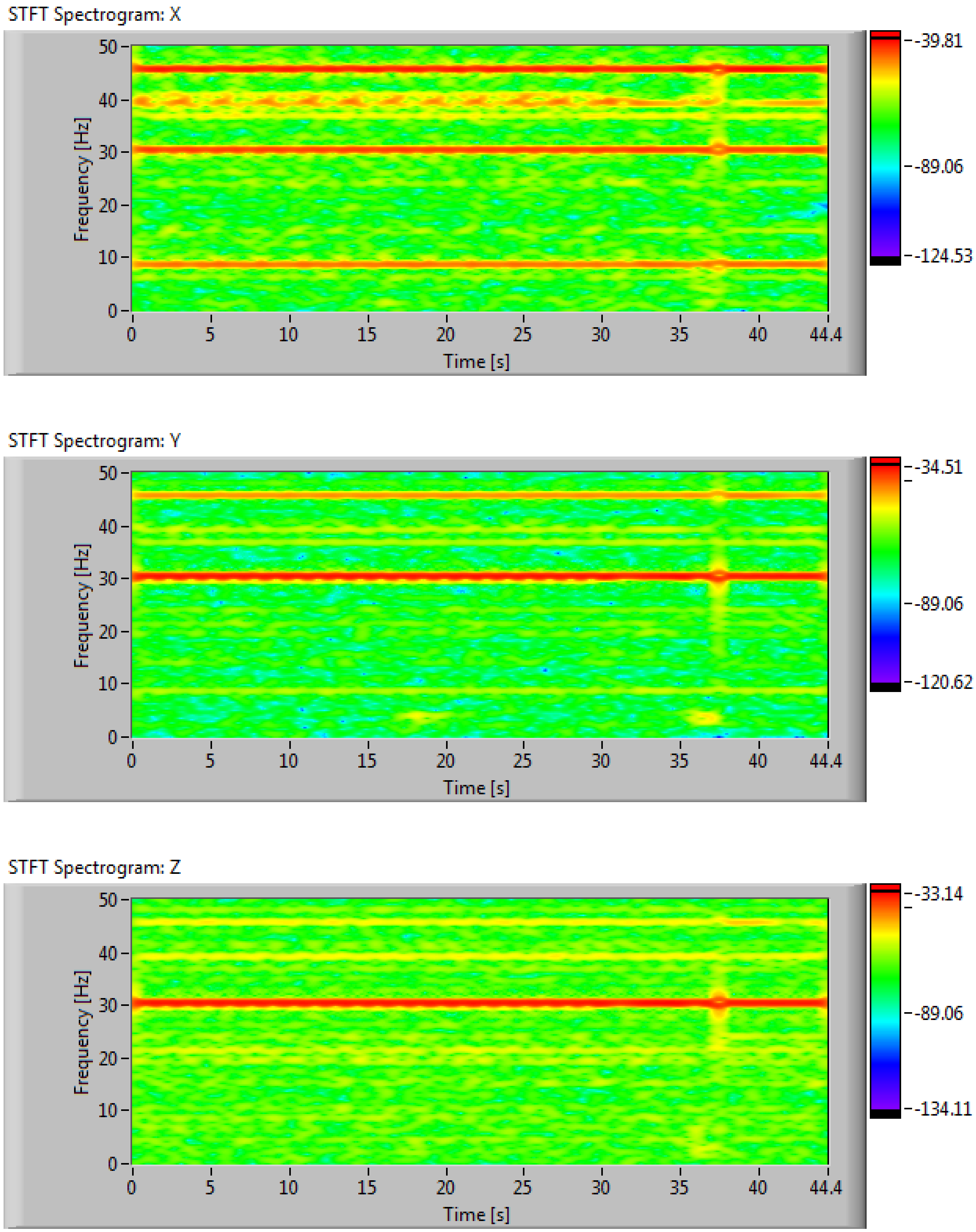


Figure 111 Sterling FD test 15, acceleration spectrogram

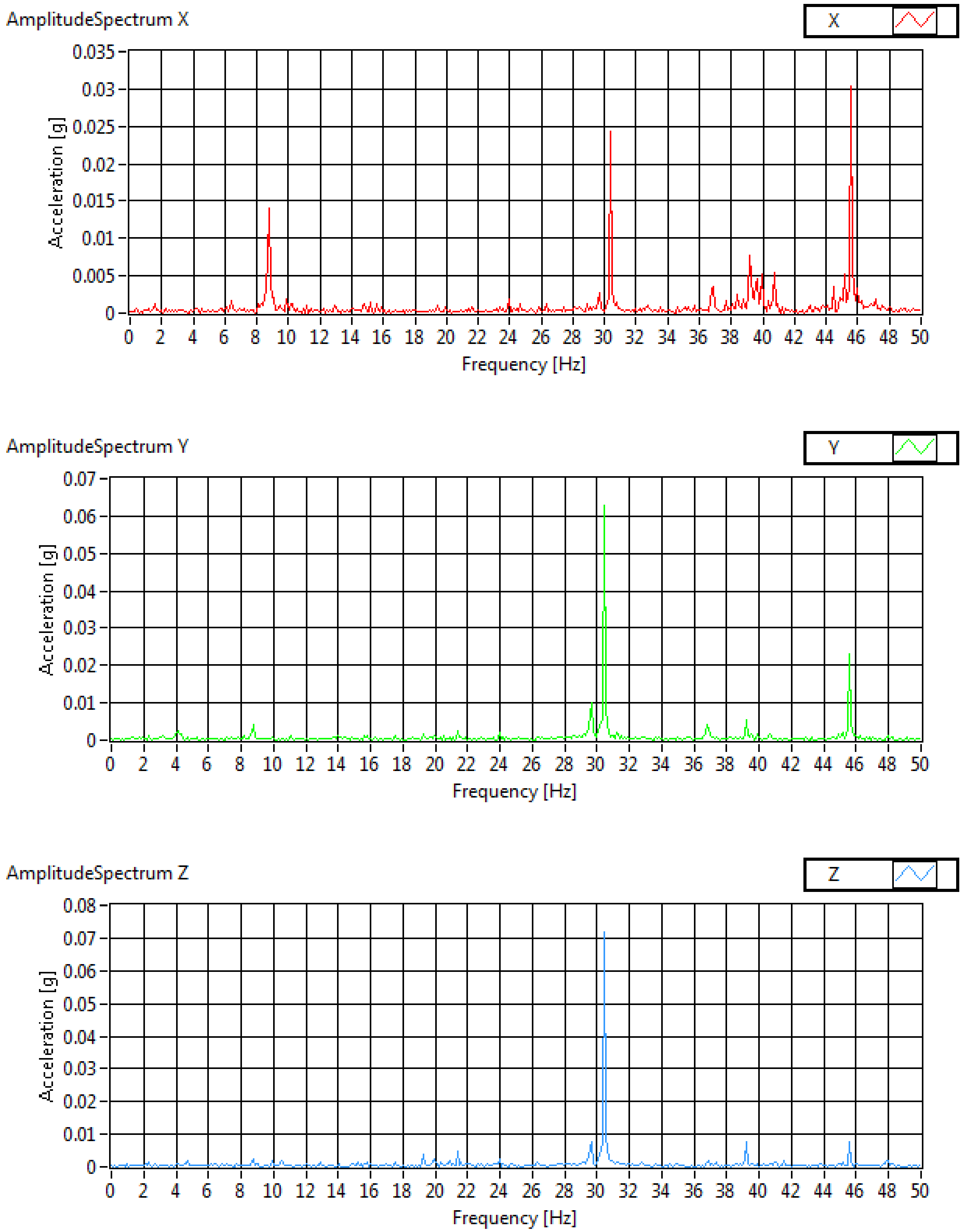


Figure 112 Sterling FD test 15, acceleration spectra

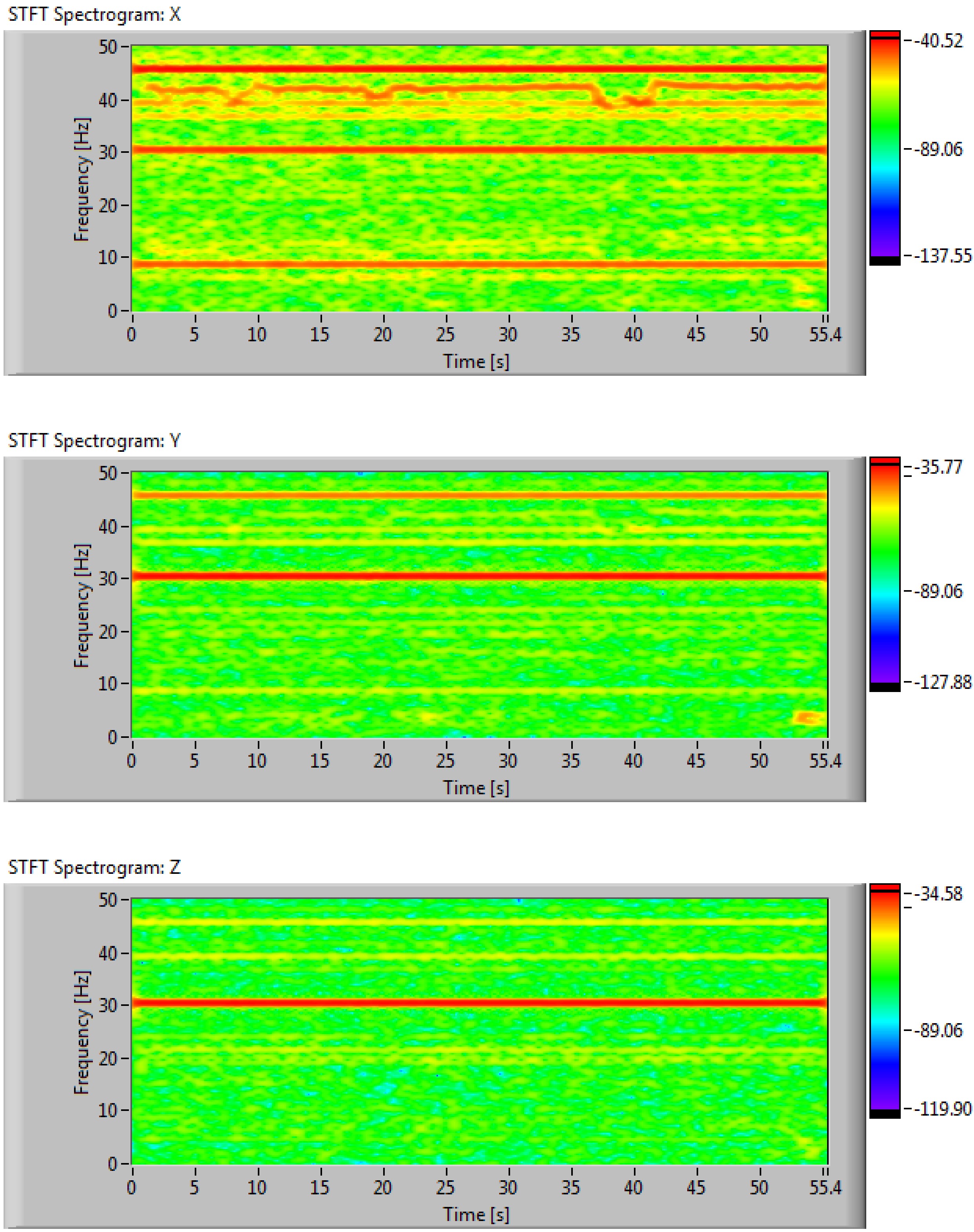


Figure 113 Sterling FD test 16, acceleration spectrogram

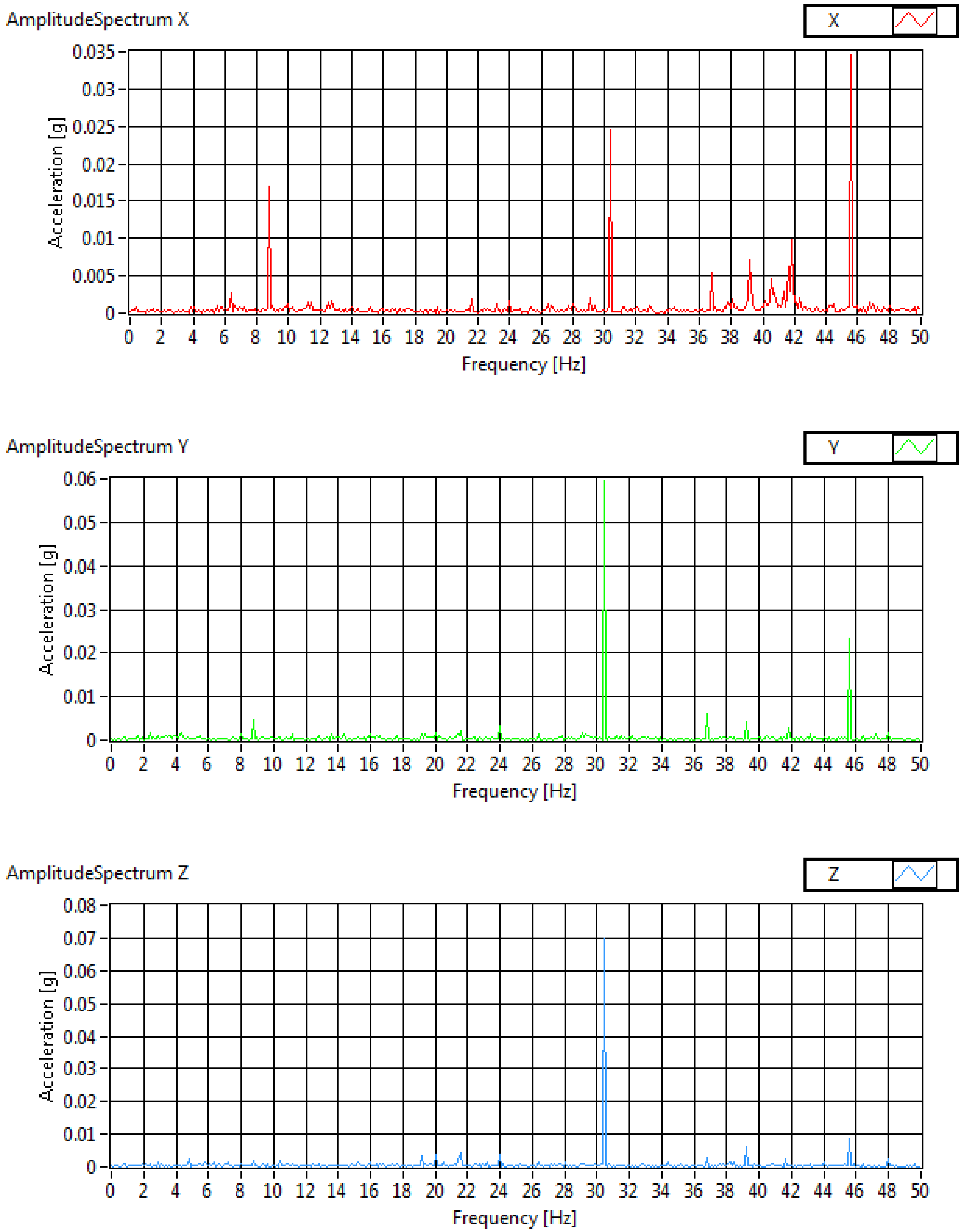
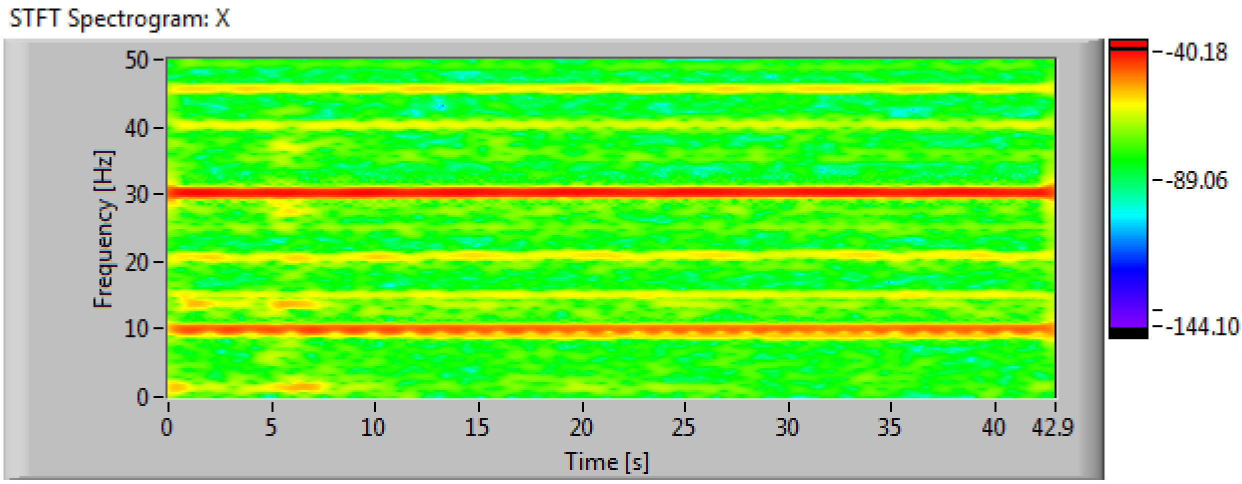
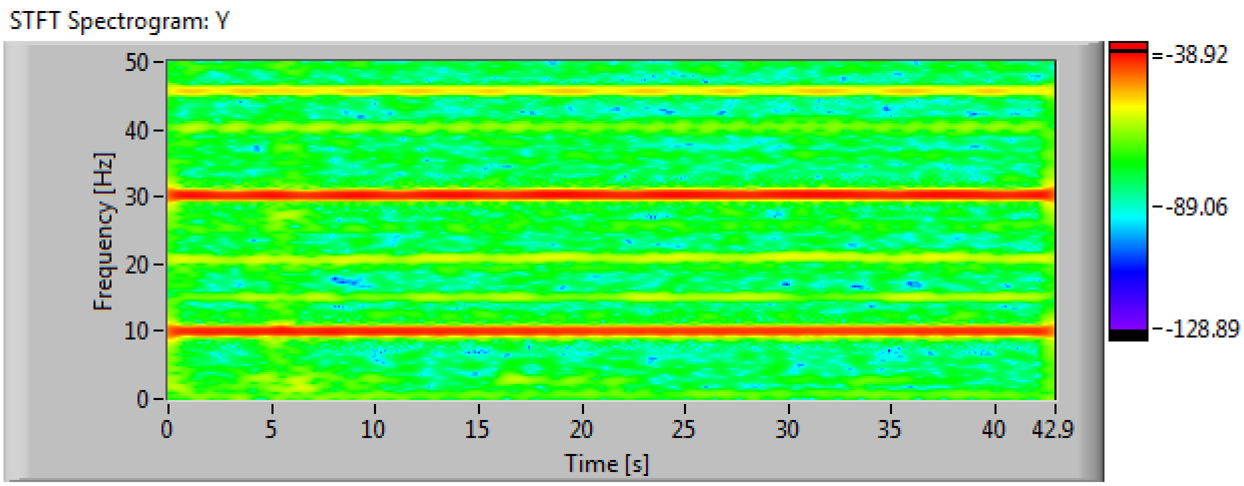


Figure 114 Sterling FD test 16, acceleration spectra





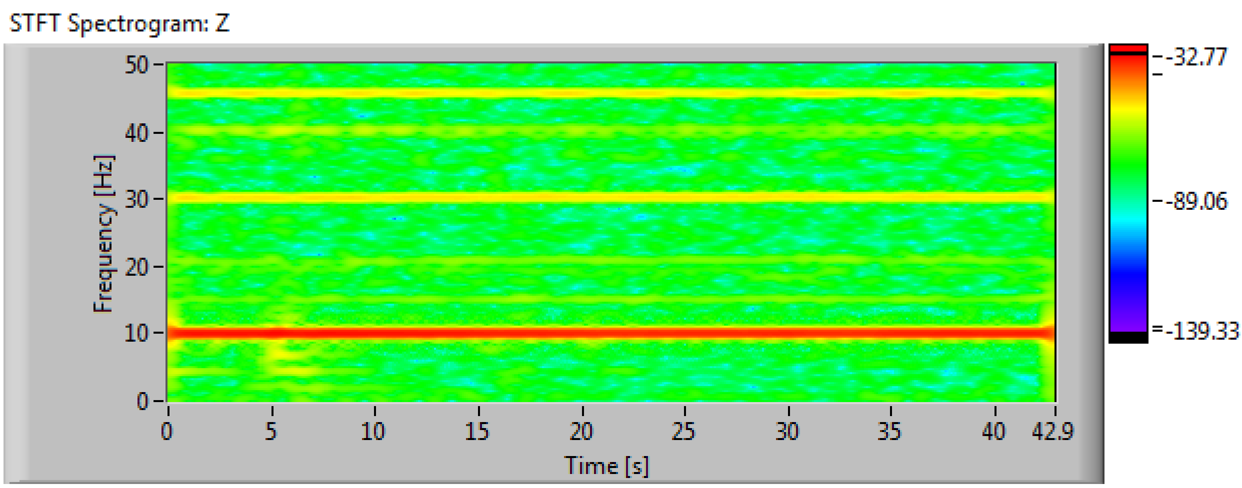


Figure 115 Sterling FD test 18, acceleration spectrogram

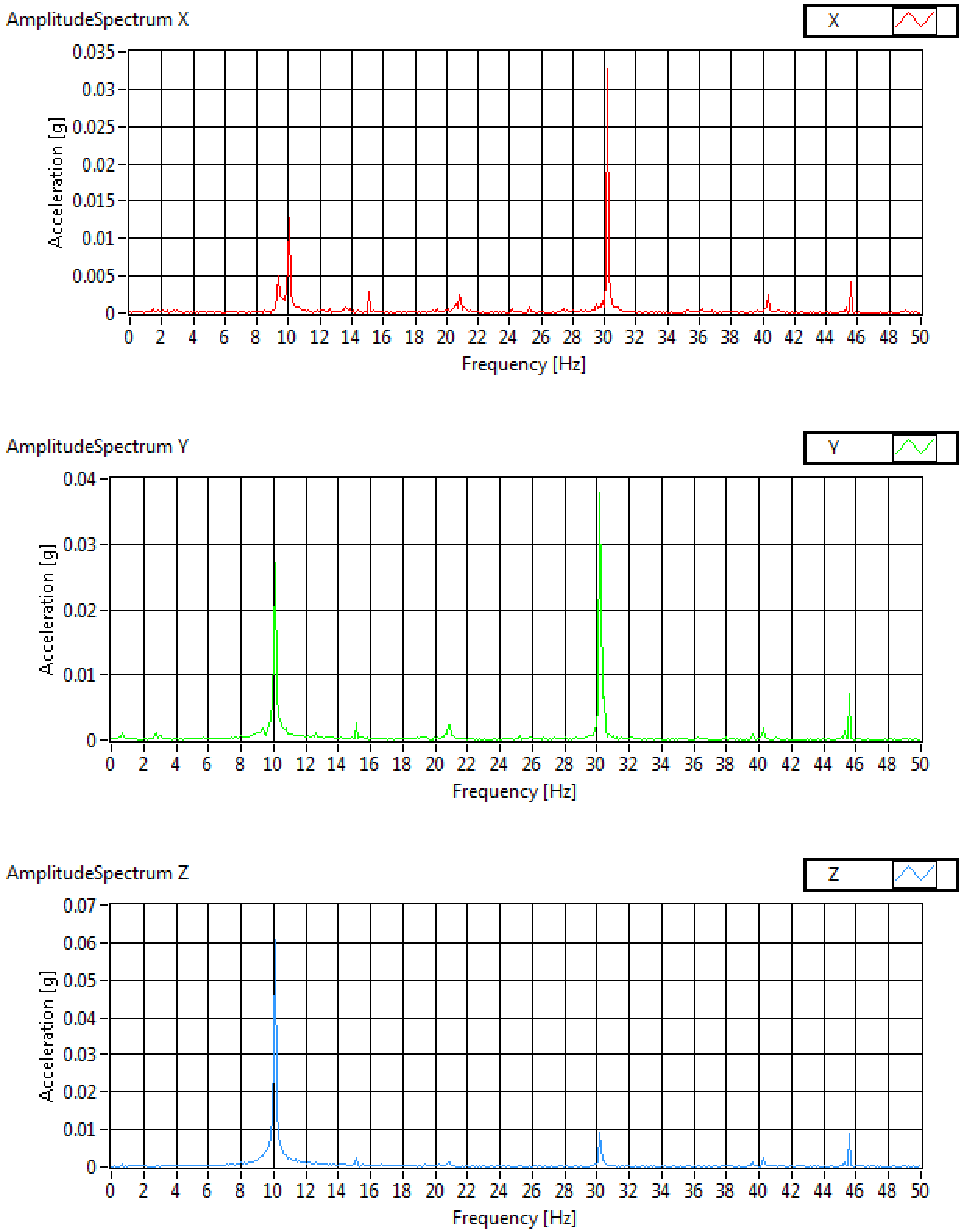


Figure 116 Sterling FD test 18, acceleration spectra

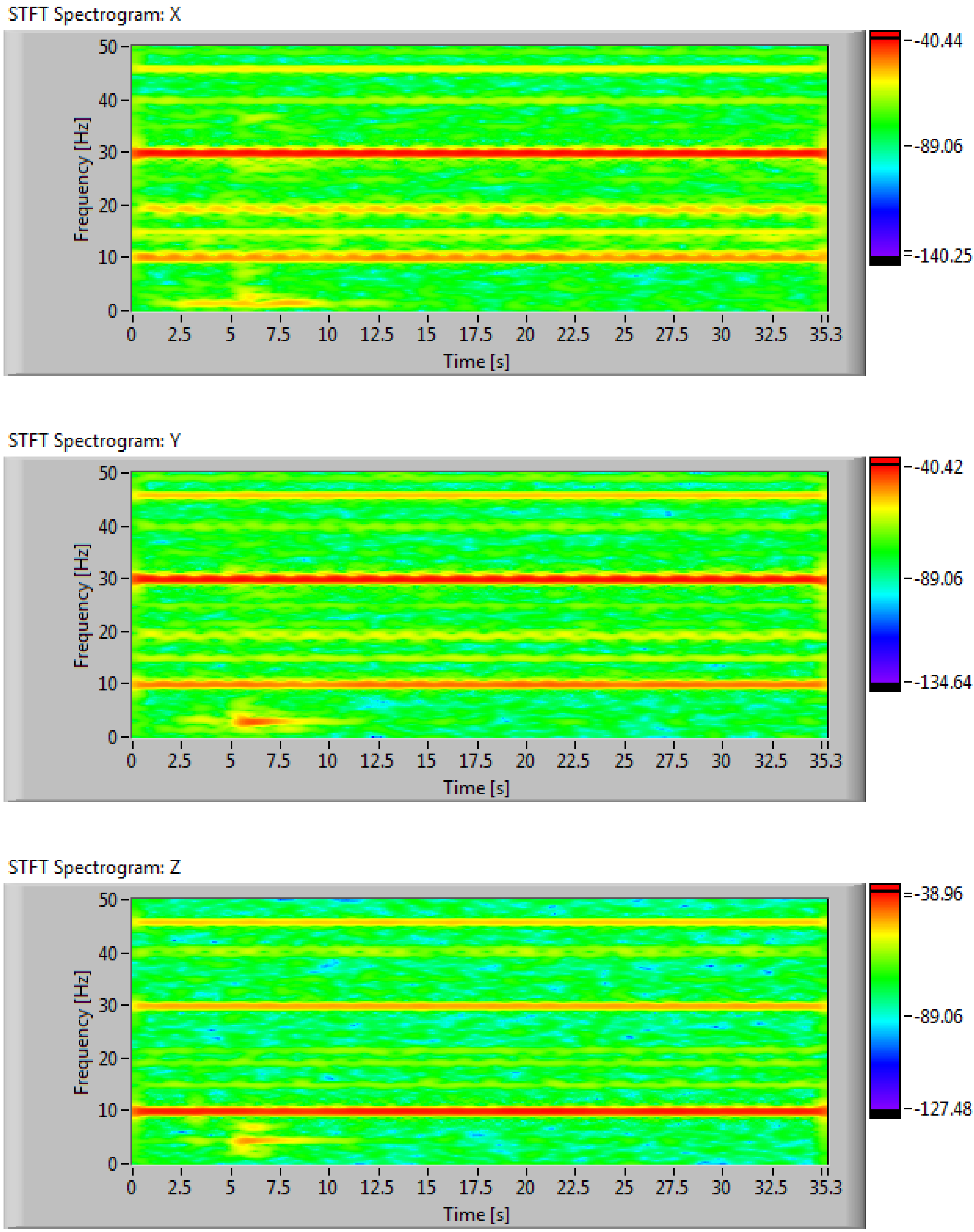


Figure 117 Sterling FD test 19, acceleration spectrogram

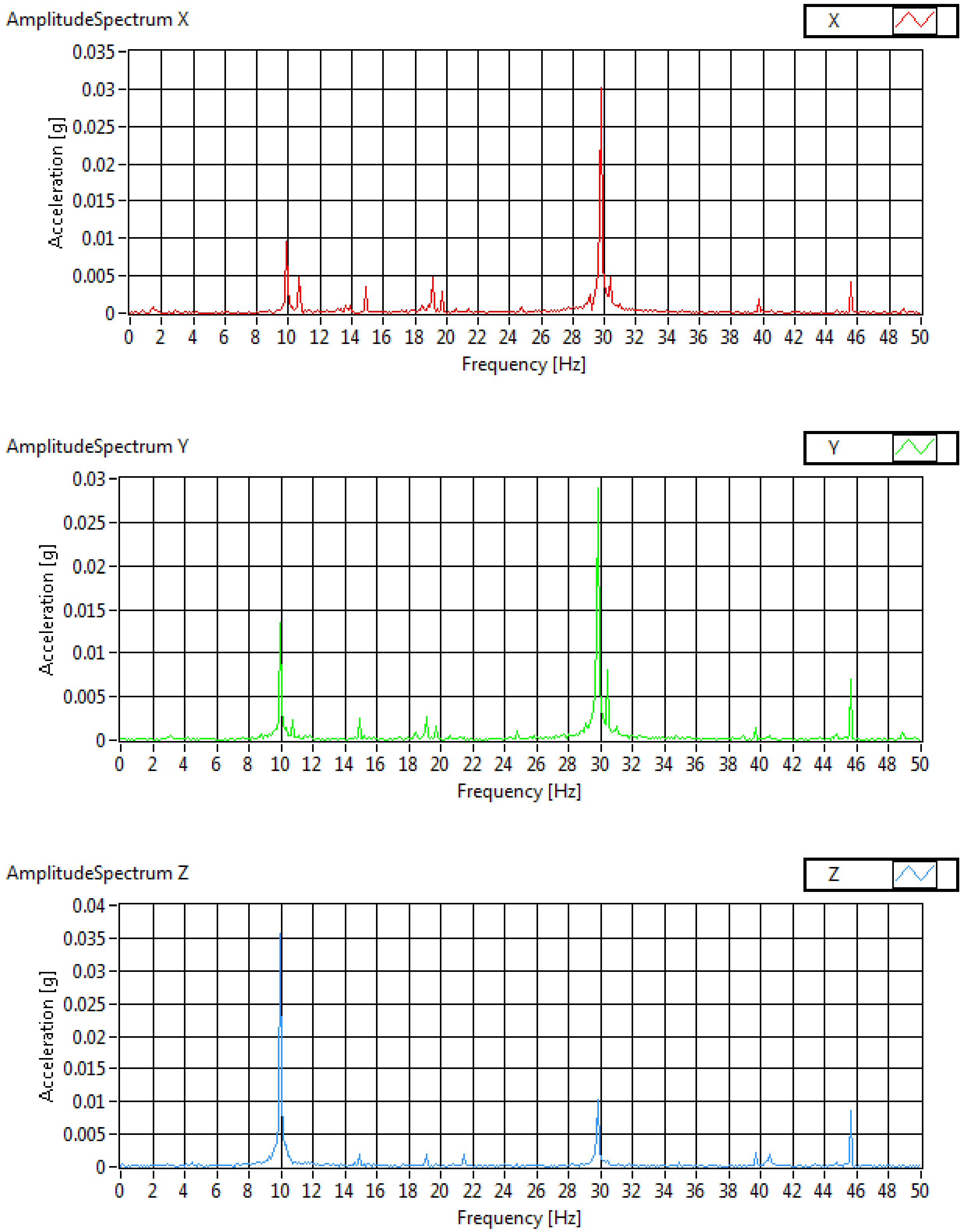


Figure 118 Sterling FD test 19, acceleration spectra

3.5.1.6 Engine 2 Type (d) Test

Table 37 Engine 2 type (d) test spectral peaks, x-axis

Test	First Peak, X		Second Peak, X		Third Peak, X		Fourth Peak, X	
No.	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]
20	29.8	0.08000	45.6	0.00600	40.6	0.00600	15.8	0.00400

Table 38 Engine 2 type (d) test spectral peaks, y-axis

Test	First Peak, Y		Second Peak, Y		Third Peak, Y		Fourth Peak, Y	
No.	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]
20	30.4	0.00530	29.8	0.00520	40.4	0.00260	45.6	0.00120

Table 39 Engine 2 type (d) test spectral peaks, z-axis

Test	First Peak, Z		Second Peak, Z		Third Peak, Z		Fourth Peak, Z	
No.	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]	[Hz]	[g]
20	29.8	0.04300	40.4	0.00800	44.8	0.00500	30.6	0.00500

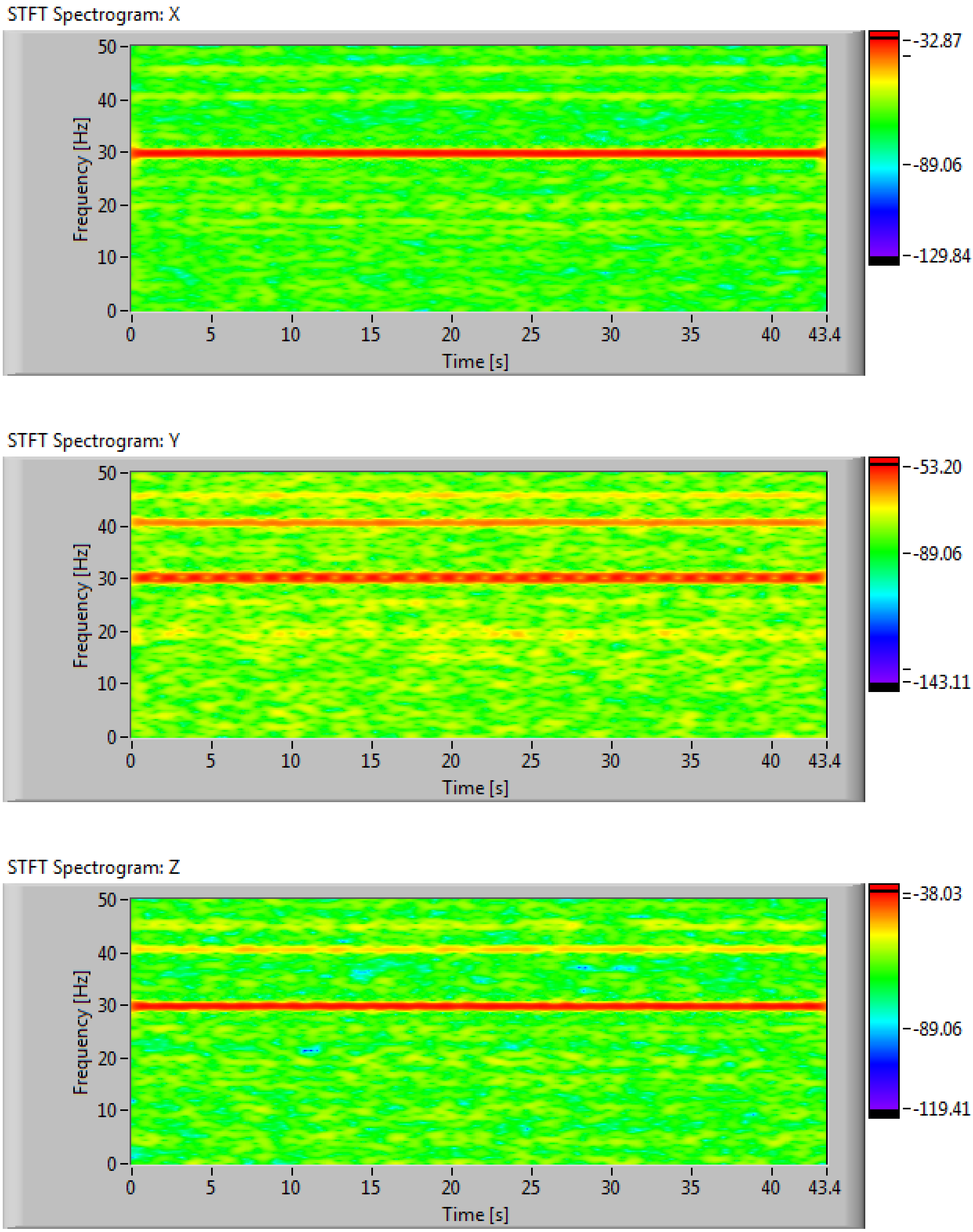


Figure 119 Sterling FD test 20, acceleration spectrogram

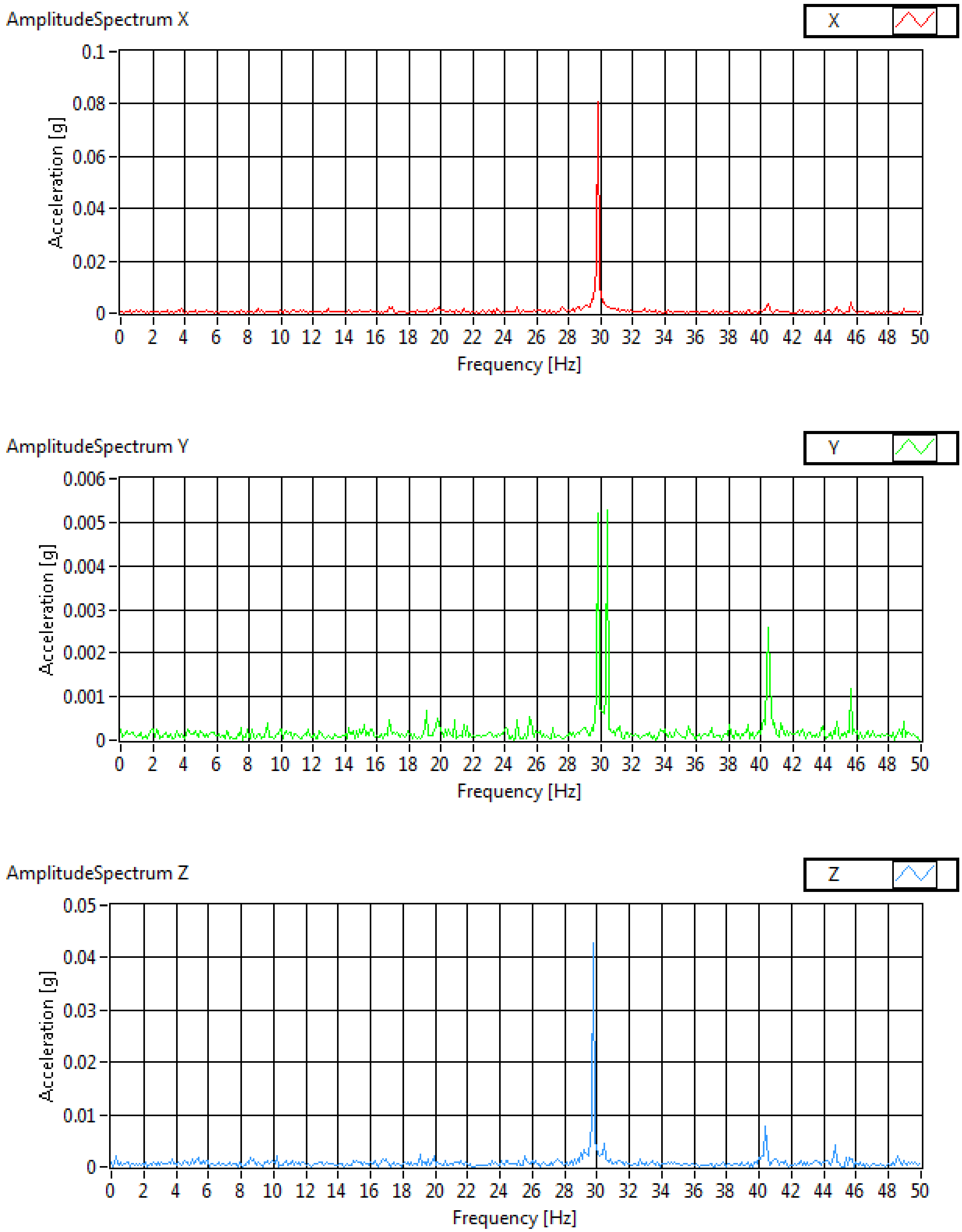


Figure 120 Sterling FD test 20, acceleration spectra

3.5.1.7 Engine 2 Type (e) Test

Table 40 Engine 2 type (e) test spectral peaks, x-axis

Test No.	First Peak, X [Hz]	[g]	Second Peak, X [Hz]	[g]	Third Peak, X [Hz]	[g]	Fourth Peak, X [Hz]	[g]
21	29.8	0.08600	40.6	0.00650	45.6	0.00600	17.2	0.00400

Table 41 Engine 2 type (e) test spectral peaks, y-axis

Test No.	First Peak, Y [Hz]	[g]	Second Peak, Y [Hz]	[g]	Third Peak, Y [Hz]	[g]	Fourth Peak, Y [Hz]	[g]
21	29.8	0.00530	30.4	0.00520	40.4	0.00320	45.6	0.00110

Table 42 Engine 2 type (e) test spectral peaks, z-axis

Test No.	First Peak, Z [Hz]	[g]	Second Peak, Z [Hz]	[g]	Third Peak, Z [Hz]	[g]	Fourth Peak, Z [Hz]	[g]
21	29.8	0.04500	40.4	0.01100	44.8	0.00500	19.2	0.00300

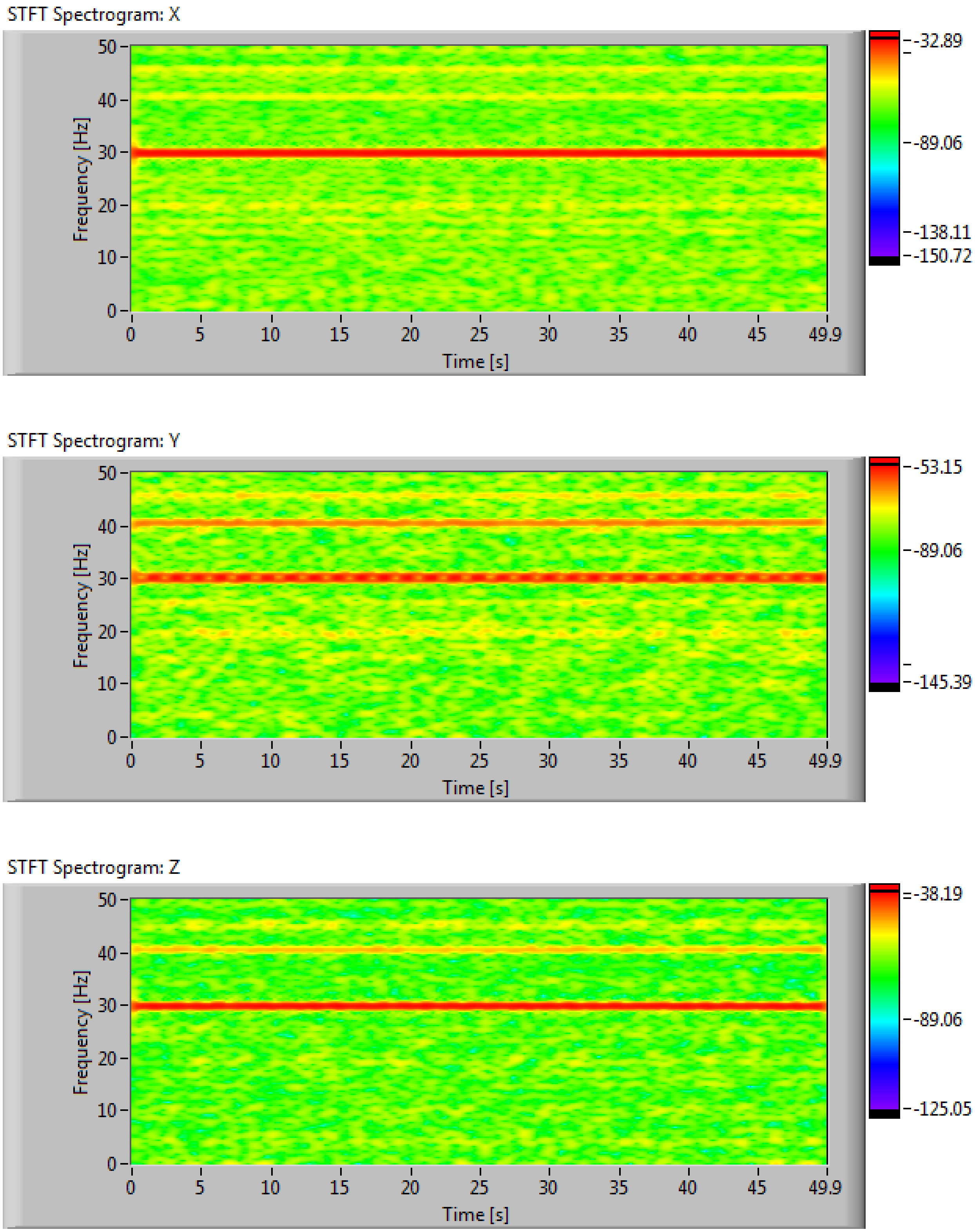


Figure 121 Sterling FD test 21, acceleration spectrogram

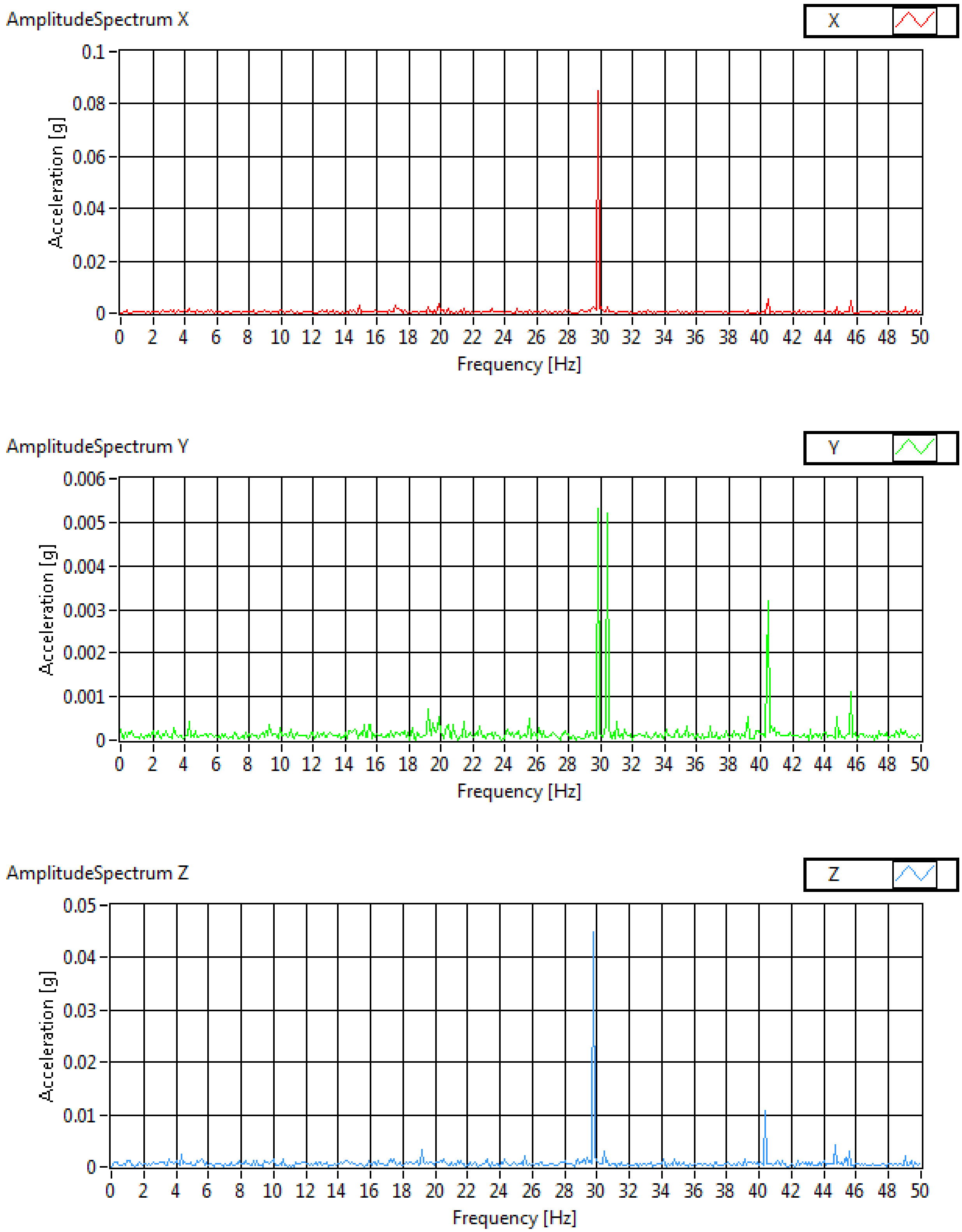


Figure 122 Sterling FD test 21, acceleration spectra

3.5.2 Summary of Results

The results of the measured accelerations of the twenty tests can be seen in Figure 123. This summary shows that the largest measured accelerations were closest to the centrifugal pump of Engine 4. Surprisingly, these values were larger than those encountered at the auxiliary generator on Engine 2.

Vibrations measured on the SCBA frames in the crew compartment of Engine 4 (tests 09, 10, and 11) were on the order of 0.04-0.05 g. The largest acceleration measured on the SCBA frame in Engine 2's crew compartment (0.17 g in test 20) was 3.5 times larger than the largest observed in Engine 4. Thus there appears to be better vibrational isolation of the crew compartment of Engine 4 as compared to Engine 2.

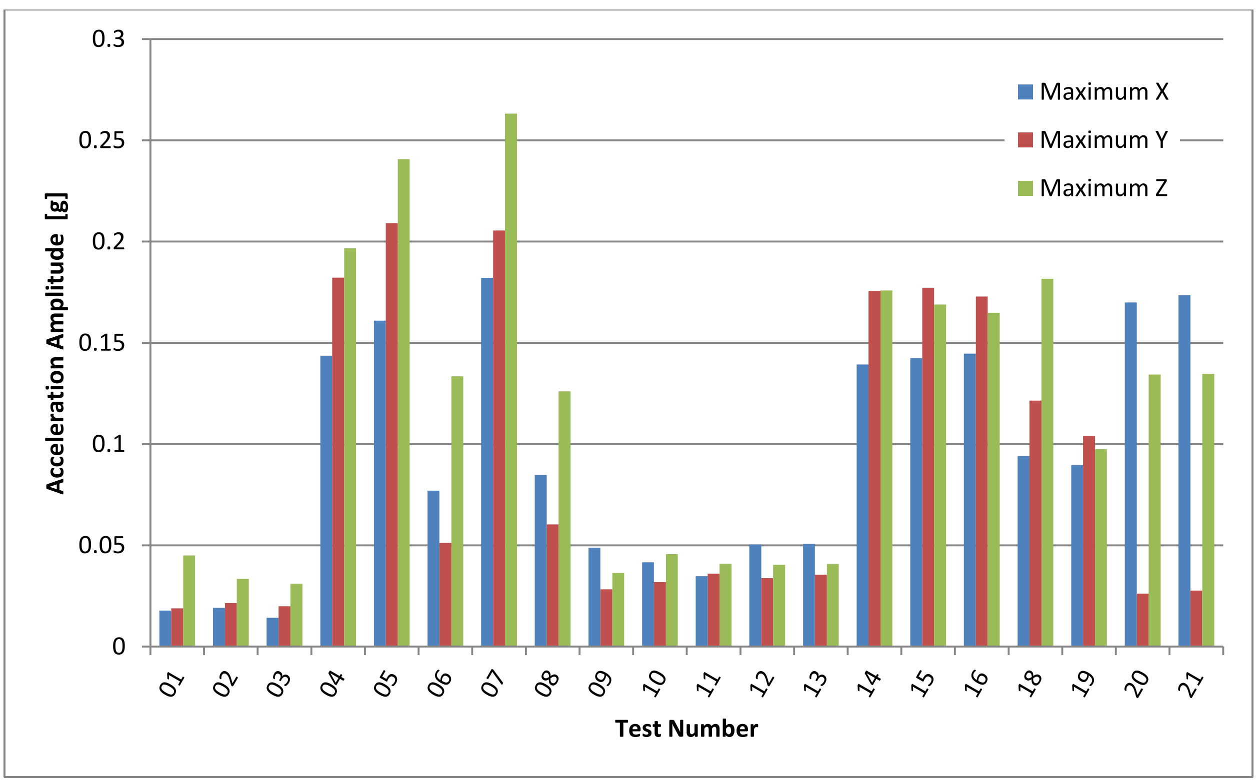


Figure 123 Maximum accelerations observed during pumping operations

Considering that the highest observed engine speed of Engine 4 was only 1,100 rpm, it is safe to assume that the 0.26 g measured at its pump panel is not the maximum possible. The observed 1,100 rpm engine speed represents only 37% of the possible range between the 750 idle and a maximum throttle of approximately 1,700 rpm. Thus the results of the straight vibration data suggest that accelerations greater than 0.26 g could be expected within a given pumper.

The peak spectral content of the given data identifies the expected frequency content of the vibrations. A word of caution should be stated here that these tests represent under-throttled pumping conditions. That is, these tests did not exhibit the kind of conditions one would expect of full pumping. That being said, the range of frequencies is probably meaningful as it illustrates that there is a wide band over which the vibrations are present.

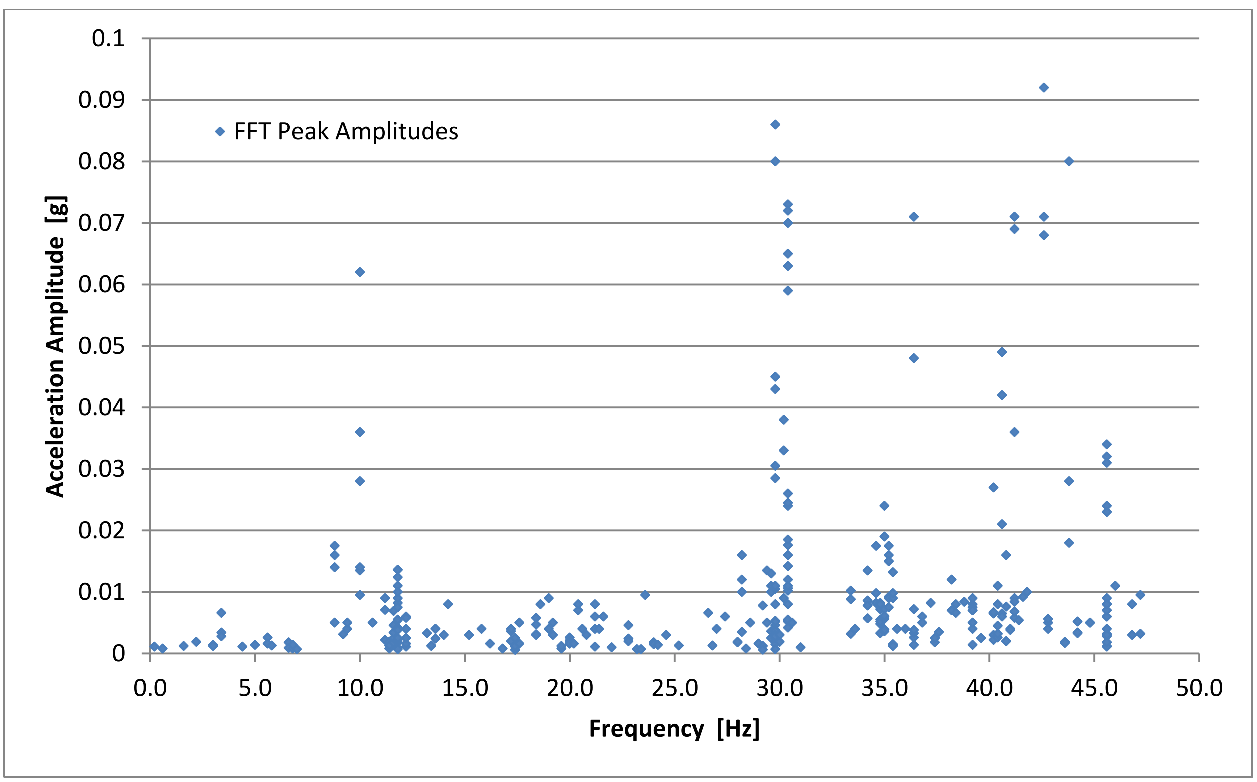


Figure 124 Plot of top four peaks of spectral content of all tests

The total number of peaks identified from the data is 348, or 116 from each axis. A plot of the data can be seen in Figure 124. The statistics of the data can be seen in Table 43 below. Recall that the bandwidth limit of the sensor was 50 Hz. Interestingly, the average frequency of the peaks was almost half that value, indicating that the distribution was spread across the band. This observation is further corroborated by the large standard deviation which was equal to half of the average. Thus any designer using this data should understand that the expected frequency content is "all over the map."

At any given time, the actual frequency value is not significant. The highest observed value of 0.092 g (at 42.6 Hz) is on the order of 35% that of the max acceleration of 0.26 g. Thus, the distribution of frequency content is, again, broadband. Over time, a broad range of frequencies will be excited.

Table 43 Statistical data of frequency from top spectral peaks

	Frequency [Hz]
Median	30.1
Mode	45.6
Average	28.1
Standard Deviation	12.4

The final chart presented (refer to Figure 125) compares the maximum frequency peaks versus the average in 2 Hz bins.

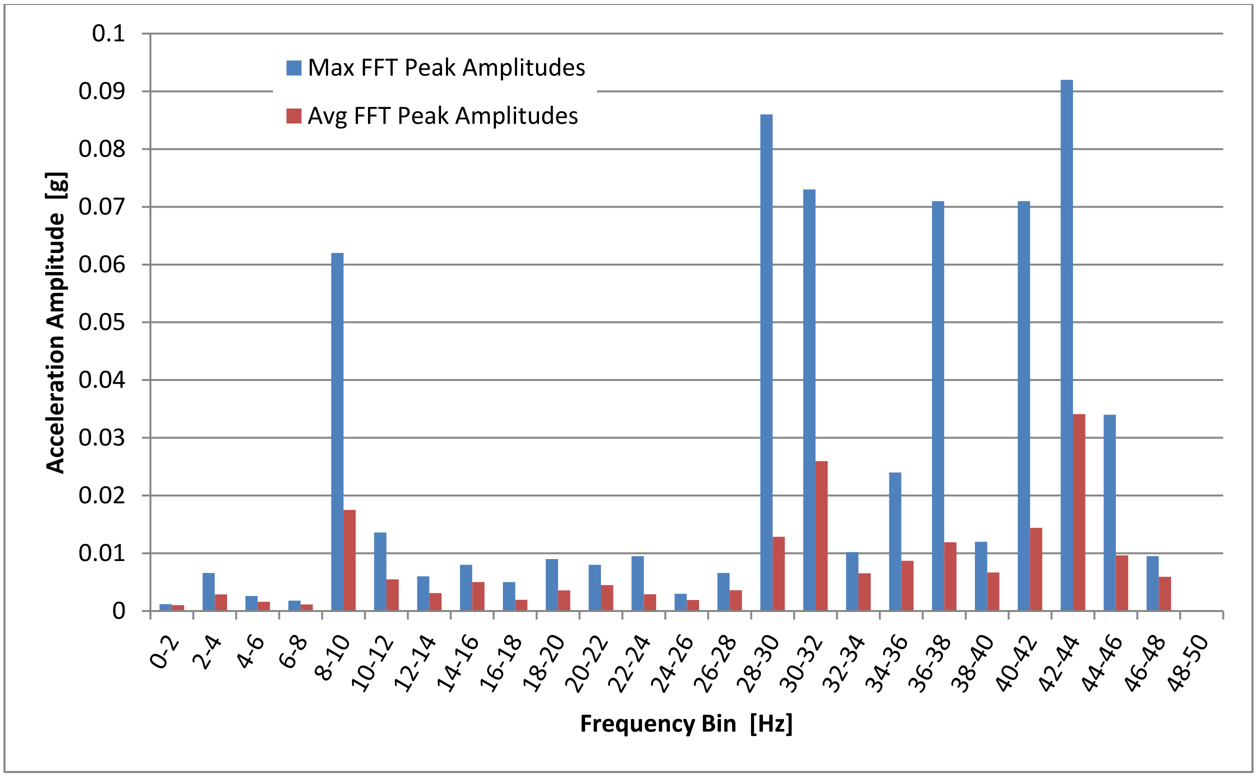


Figure 125 Maximum and average FFT peaks by 2 Hz bin

3.6 Results and NFPA Standards

Significantly more data is required to justify a suggestion to the NFPA for changes to design and/or test strategies in NFPA 1901. However, a preliminary analysis suggests that the rigid mounting of SCBAs is a potential source of vibration conduction. Recall that the largest amplitude of acceleration measured during pumping operations was 0.26 g. While this value does not take into account apparatus driving and any variance of road conditions, it is certainly a large value. It is approximately 2.5 times larger than the 0.1 g accelerations experienced in ambulances.[63] It should be further noted that these are not equal comparisons: the fire apparatus under test was stationary and the ambulance under test was driving.

Without exhaustive data, a tentative solution perhaps would be to word the bracket definitions such that they cushion the SCBAs to suppress vibrations up to approximately twice the largest value, or 0.5 g. Above this level, it would be acceptable for the brackets to rigidly prevent movement of the units. Use of such a non-linear cushioning strategy, would not affect the crash worthiness. However, the vibration coupling for normal day-to-day operations could be greatly reduced.

A full study of the most representative group of fire apparatus would provide the comprehensive type of data necessary to define the vibration suppression and rigid clamping threshold. This Major Qualifying Report provides the framework and methodology necessary to experimentally determine this threshold.

3.6.1 Additional Research Topics

The development of a bracket that both cushions and retains an SCBA over different ranges of acceleration loading may well be of the extent worthy of an additional MQP study. Should this be of interest, the following list is provided as a framework for the proposed work:

1. Literature review of applicable standards (such as NFPA 1901 and NFPA 1981 *Standard on Open-Circuit Self-Contained Breathing Apparatus for Emergency Services, 2013 ed.*)
2. Review and characterization of the existing bracket designs and methodology
3. Review and characterization of the SCBAs
    a. Six major US brands: Draeger, Honeywell/Sperian, International Safety Instruments (ISI), Interspiro Mine Safety Appliances (MSA), Scott Safety
    b. Major cylinder manufacturers: Structural Composite Industries (SEI) or Luxfer
4. Design of a universal bracket
    a. 0.0 to 0.5 g: Vibration Isolation
    b. 0.5 to 9.0 g: Rigid restraint of SCBA
    c. Proposed bracket specification wording for NFPA 1901, if applicable
5. Reporting
    a. SCBA design parameters data: weights, sizes, configurations, etc.
    b. Bracket design: CAD, mechanical drawings, assembly documentation, etc.
    c. Write up of lessons learned
    d. Presentation to NFPA in Quincy or to a TC meeting of NFPA 1901

CHAPTER 4: Concluding Remarks

The first objective of this Major Qualifying Project was a literature review of the types and specifications of fire apparatus. The second objective was development of a sensor and data acquisition system capable of measuring vibrations of representative fire apparatus. The final objective was to use the sensor and data acquisition system to measure and analyze actual vibration, identifying maximum acceleration levels and frequency content.

4.1 Literature Review

The review stage of the MQP included the identification of various types of apparatus. Relevant DOT and NFPA specifications were identified in detail. A comprehensive list of fire apparatus manufacturers was provided. Additional discussion was provided on the tasks and functions of modern day fire apparatus. A preliminary discussion of vibration and its effects on equipment and personnel was provided.

4.2 Sensor and Data Acquisition System

The scientific methodology and experimental method for data collection was defined. The original work plan called for the use of a high-end accelerometer for data recording. Given time and schedule constraints and the high cost of rental, a low-cost alternative to the sensor was developed and implemented. The system was then calibrated and validated prior to use on actual fire apparatus.

4.3 Data Collection and Analysis

A training exercise involving pumping evolutions by the Sterling Fire Department provided an ideal opportunity to gather vibration data from pumper apparatus. A series of seven different types of tests was conducted on two different pumper apparatus. The data from these tests was analyzed and presented in tabular and graphical format. The results and methodology employed provide a basis for further research into this important issue regarding safety equipment.

4.4 Conclusion and Recommendations

This MQP provides the first step in taking a more scientific and thorough approach towards a resolution of the adverse effects of vibration on the electronic equipment used by firefighters and emergency responders. Additional research is desired to completely characterize the vibrational environment of modern fire apparatus. Pumping operations have been characterized herein, however, vibration occurring in different operating conditions such as transport as well as other types of apparatus are still of interest. With the possibility of future NFPA specifications requiring vibration testing, baseline data that more accurately replicates the actual environment would be desired.

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APPENDICES

Appendix A: Sensor Fabrication Instructions

The following CAD drawings contain step by step instructions necessary to fabricate a similar sensor to the one used in this MQP.

REVISION HISTORY				
REV	DESCRIPTION	DATE	AUTH	APPROVED
01	Initial Drawing	04/17/2012	ZSH	

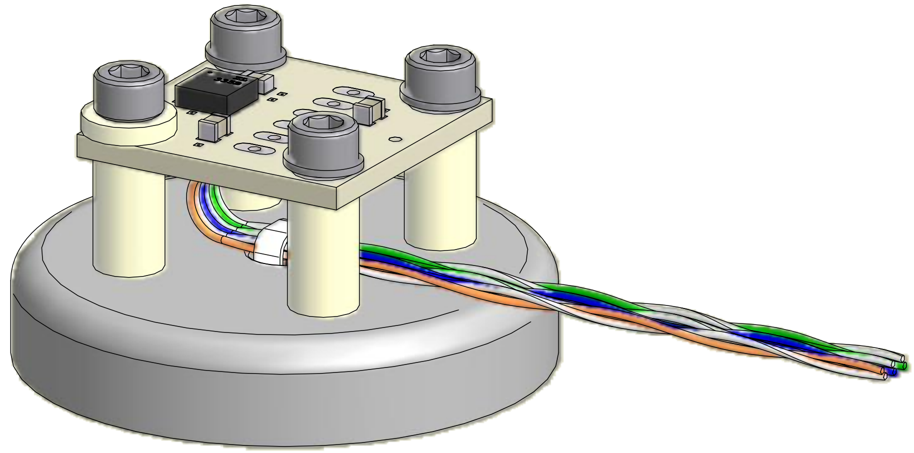

FIGURE 1
SCALE 2 : 1

Notes:

1. The following are instructions for assembly of the 50 Hz version ADXL335 Prototyping Board vibration sensor.

Parts List				
ITEM	QTY	PART NUMBER	DESCRIPTION	VENDOR
1	1	RB-30	Steel Cup Holding Magnet Nickel-Plated	MagnetShop.com
2	1	Wire Harness	Category 5 Cable	Multiple
3	1	7130K12	Cable Tie 4" Length, 0.10" Width	McMaster-Carr
4	4	94639A708	#4 5/16" Stand-Off, Nylon 6/6	McMaster-Carr
5	1	876-1002-ND	ADXL335 Prototyping Board	Digi-Key
6	3	92146A530	#4 Lock Washer, 21" OD, .02" min Thick, 18-8 SS	McMaster-Carr
7	3	92185A109	4-40, 7/16", Socket Cap Screw, 18-8 SS	McMaster-Carr
8	1	90295A045	#4 Washer, 0.25" OD, 0.05"-0.07" Thk, Nylon 6/6	McMaster-Carr
9	1	92185A110	4-40, 1/2", Socket Cap Screw, 18-8 SS	McMaster-Carr

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Scale: DO NOT SCALE	Part Number / Part Description: Sensor / DKSB1002A		
Date: 4/17/2012	Project:		
Material: See Notes	Designer: ZSH	Revision:	
Finish: See Notes	Approved By:	Dwg. Number: 1 of 6	

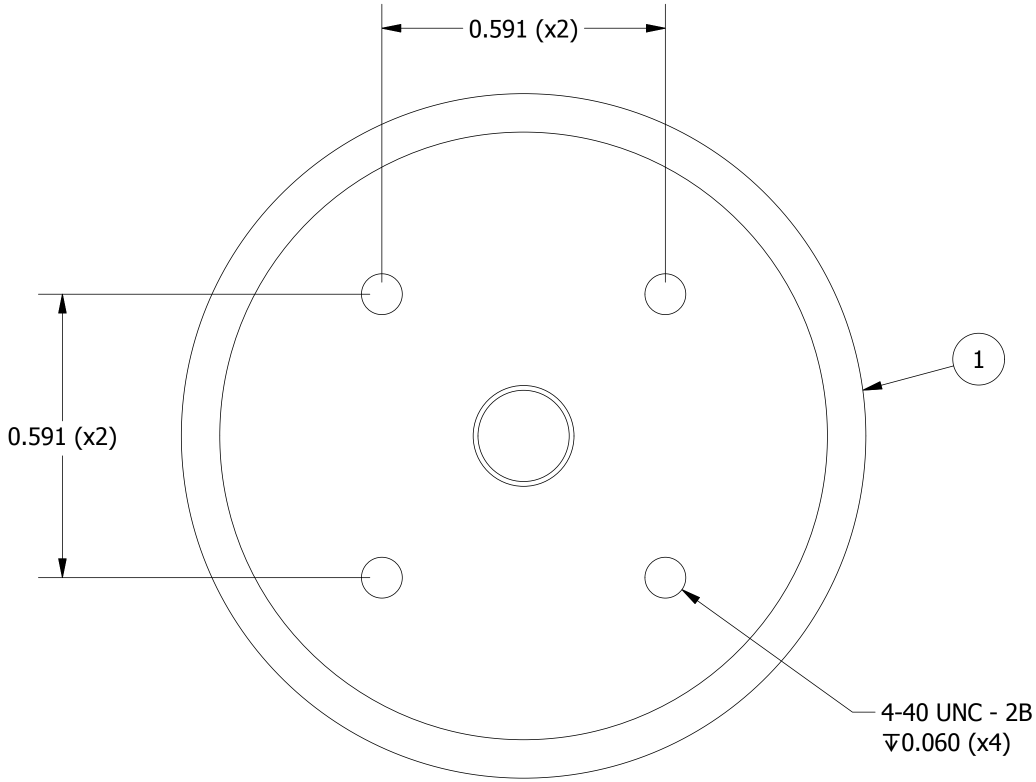

FIGURE 2
SCALE 2.5 : 1

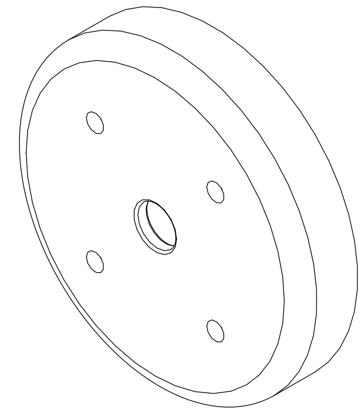

FIGURE 3
SCALE 1.5 : 1

INSTRUCTIONS

1.) Drill and tap ITEM 1 as shown in FIGURES 2 and 3.

2.) Use a #43 drill bit for the drill operation.

3.) Exercise caution as magent ceramic is prone to fracture. Drill SLOWLY.

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8 7 6 5 4 3 2 1

D

INSTRUCTIONS

1.) Strip outer insulator of ITEM 2 approximately 8 inches from end.

2.) Affix three of the four twisted pairs of ITEM 2 to ITEM 1 as shown in FIGURE 4. Leave approximately 0.85" of wire past ITEM 2.

3.) Secure using ITEM 3 such that the latch receptacle is located inside the cup of ITEM 1.

4.) Strip ends of each wire approximately 0.10" leavin approximately 0.75" of insultaed wire to perform the bend.

C

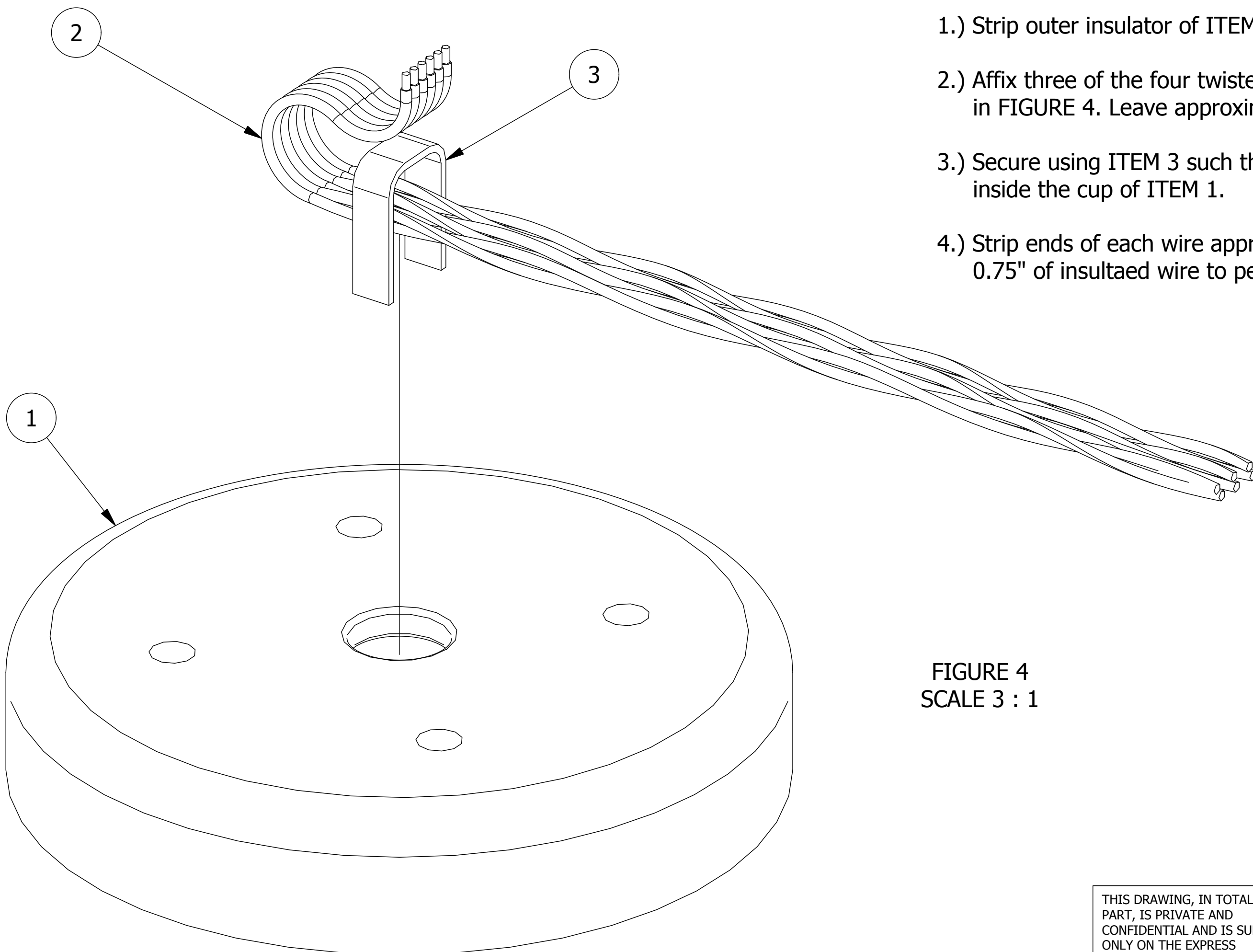

FIGURE 4
SCALE 3 : 1

B

A

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Material: See Notes	Designer: ZSH		Revision:
Finish: See Notes	Approved By:		Dwg. Number: 3 of 6

8 7 6 5 4 3 2 1

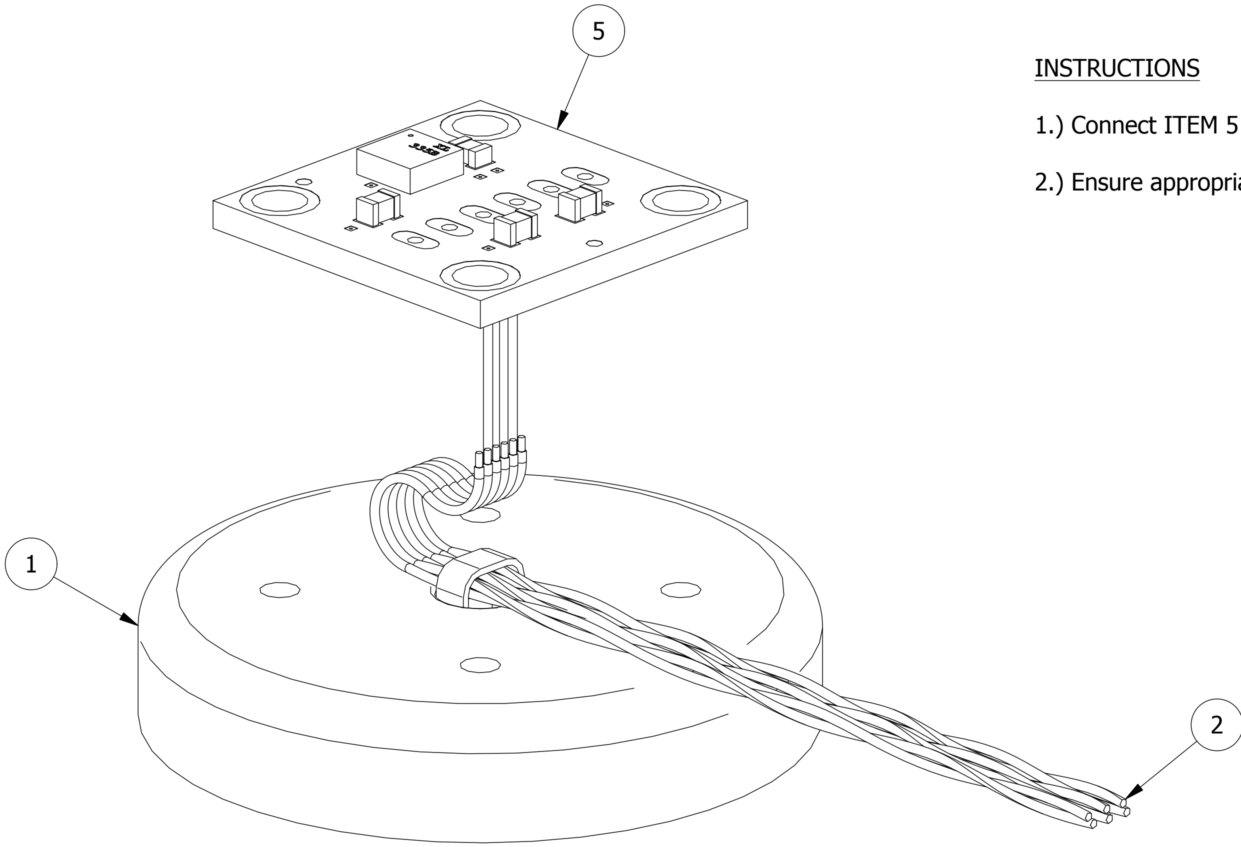

FIGURE 5
SCALE 2.5 : 1

INSTRUCTIONS

1.) Connect ITEM 5 to ITEM 2 as shown in FIGURE 5. Solder the wires.

2.) Ensure appropriate pinout using the electrical schematic.

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Material: See Notes	Designer: ZSH — Revision:
Finish: See Notes	Approved By: — Dwg. Number: 4 of 6

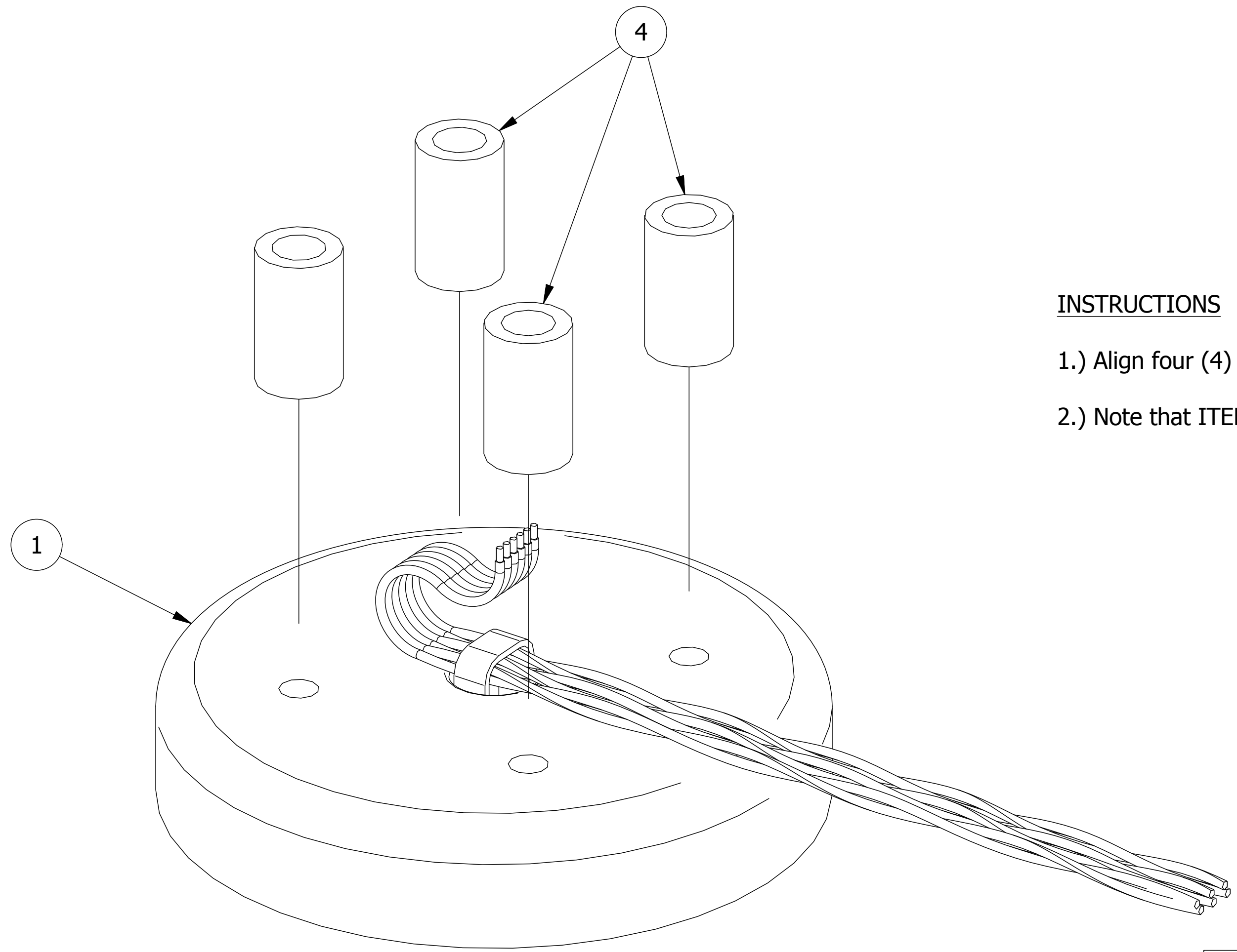

FIGURE 6
SCALE 2.5 : 1

INSTRUCTIONS

1.) Align four (4) instances of ITEM 4 as shown in FIGURE 6.

2.) Note that ITEM has been ommited for clarity.

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Date: 4/17/2012	Project:
Material: See Notes	Designer: ZSH / Revision:
Finish: See Notes	Approved By: / Dwg. Number: 5 of 6

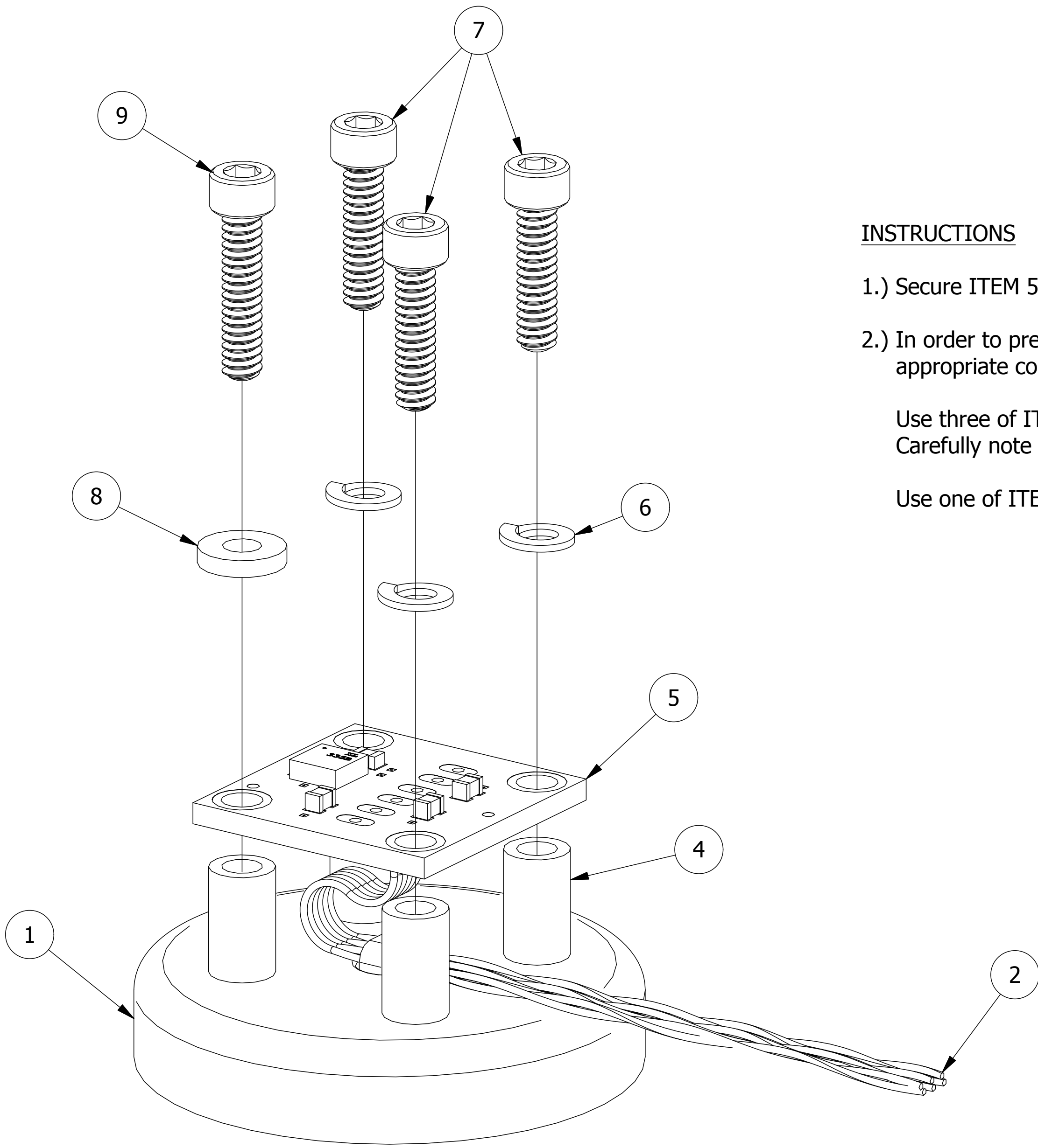

FIGURE 7
SCALE 2 : 1

INSTRUCTIONS

1.) Secure ITEM 5 to ITEM 1 as shown in FIGURE 7.

2.) In order to prevent a short to one of the PCB fiducials, ensure that the appropriate combinations of screws and washers are used as noted below.

Use three of ITEM 6 in conjunction with three of ITEM 7.
Carefully note the three locations of these ITEMS.

Use one of ITEM 8 in conjunction with one of ITEM 9.

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Date: 4/17/2012	Project:
Material: See Notes	Designer: ZSH / Revision:
Finish: See Notes	Approved By: / Dwg. Number: 6 of 6

Appendix B: Analog Devices ADXL335 Prototyping Board Data Sheet.

The following pages contain the Digi-Key data sheet for the ADXL335 accelerometer prototyping board used in this experiment. This lists the capacitor values used which determines the bandwidth of the sensor. Specifics of component values can be found in the ADXL355 data sheet. Refer to Appendix C: Analog Devices ADXL335 Data Sheet for further discussion.[64]

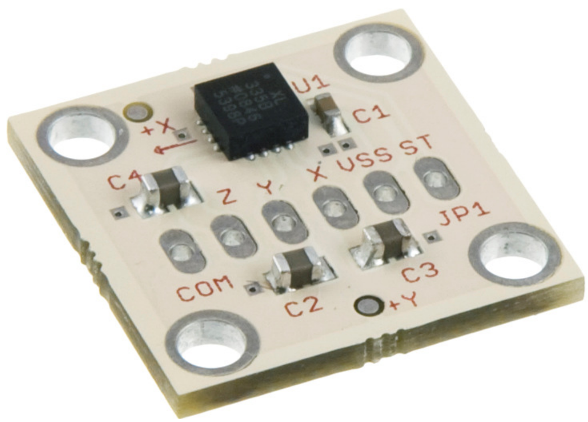
DKSB1002A

Analog Devices ADXL335 Prototyping Board

01 Nov 2009

Features

Analog Devices ADXL335 3-axis accelerometer



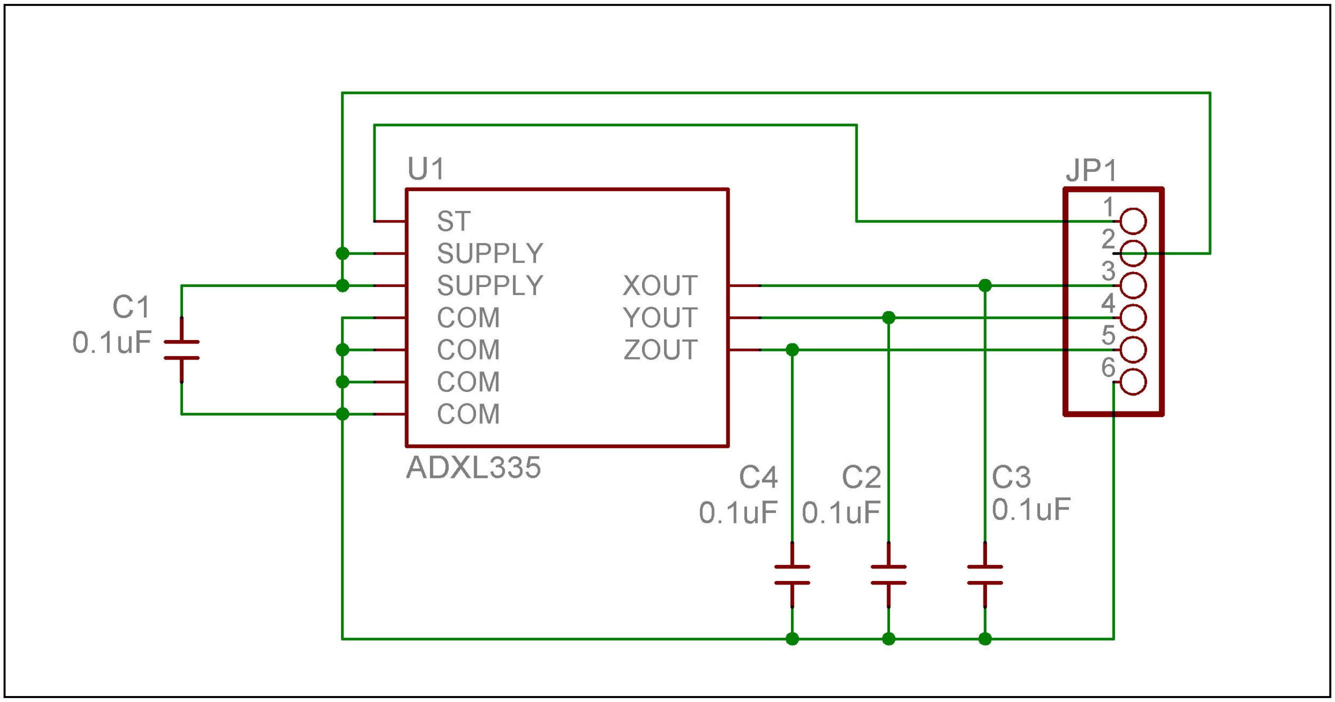
Functional Description

The DKSB1002B is a low cost, minimal implementation of the Analog Devices ADXL335 three-axis accelerometer. It provides a convenient means of making mechanical and electrical connections to the ADXL335, facilitating its use when the surface mount form factor of the device might otherwise be inconvenient.

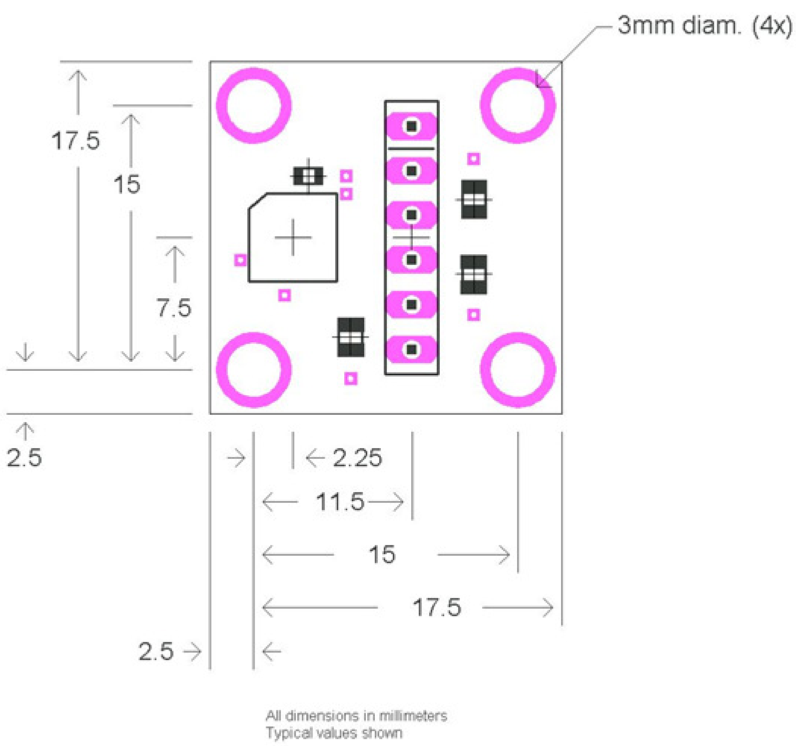
The DKSB1002B is modeled after the Analog Devices EVAL-ADXL335Z evaluation board for the ADXL335. Both boards are approximately 20mm square with mounting holes on a 15mm spacing. The orientation and location of the accelerometer and 6-pin connector are common to both boards as well. The locations of the output filter capacitors differ from those on the EVAL-ADXL335Z in order to facilitate manual replacement of these components if a change in their value is desired.

Please refer to the ADXL335 datasheet at www.analog.com for electrical specifications and application information.

Schematic



Physical Dimensions



Bill of Materials

Ref-Des	Digi-Key P/N	Mfr P/N	Description
C1	PCC2277CT-ND	ECJ-1VB1E104K	0.1uF ceramic cap X7R 25V 0603
C2,C3,C4	PCC1828CT-ND	ECJ-2VB1E104K	0.1uF ceramic cap X7R 25V 0805
U1	ADXL335BCPZ-RL7CT-ND	ADXL335BCPZ-RL7	3-axis acccelerometer
JP1	SAM1038-06-ND	SAM1038-06-ND	0.1" header, 0.025" sq. pin, 6 pos

Hardware Revision History

Rev A:

- Initial Revision

Rev B:

- Cosmetic changes to bottom silkscreen layer
- Populated C2,C3,C4 with 0.1uF capacitor
- Populated JP1
- Updated documentation to reflect hardware changes

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Appendix C: Analog Devices ADXL335 Data Sheet

The following pages contain the Analog Devices data sheet for the ADXL335 accelerometer used in this experiment.[65]

Small, Low Power, 3-Axis ±3 *g* Accelerometer

ADXL335

FEATURES

3-axis sensing
Small, low profile package
4 mm × 4 mm × 1.45 mm LFCSP
Low power : 350 μA (typical)
Single-supply operation: 1.8 V to 3.6 V
10,000 *g* shock survival
Excellent temperature stability
BW adjustment with a single capacitor per axis
RoHS/WEEE lead-free compliant

APPLICATIONS

Cost sensitive, low power, motion- and tilt-sensing applications
Mobile devices
Gaming systems
Disk drive protection
Image stabilization
Sports and health devices

GENERAL DESCRIPTION

The ADXL335 is a small, thin, low power, complete 3-axis accelerometer with signal conditioned voltage outputs. The product measures acceleration with a minimum full-scale range of ±3 *g*. It can measure the static acceleration of gravity in tilt-sensing applications, as well as dynamic acceleration resulting from motion, shock, or vibration.

The user selects the bandwidth of the accelerometer using the C_X, C_Y, and C_Z capacitors at the X_{OUT}, Y_{OUT}, and Z_{OUT} pins. Bandwidths can be selected to suit the application, with a range of 0.5 Hz to 1600 Hz for the X and Y axes, and a range of 0.5 Hz to 550 Hz for the Z axis.

The ADXL335 is available in a small, low profile, 4 mm × 4 mm × 1.45 mm, 16-lead, plastic lead frame chip scale package (LFCSP_LQ).

FUNCTIONAL BLOCK DIAGRAM

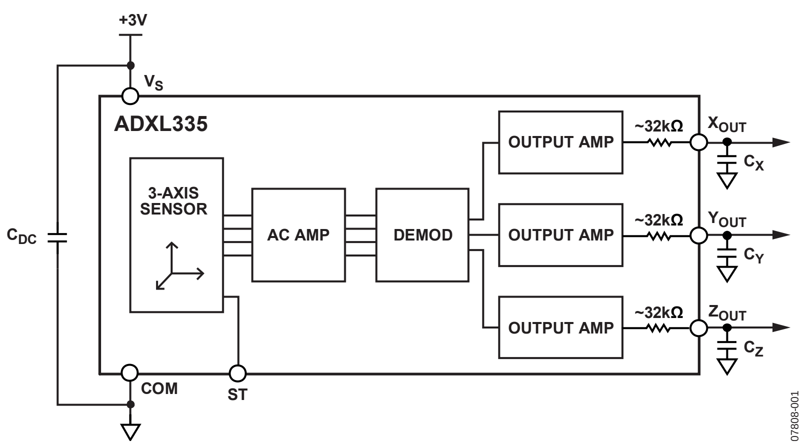

Figure 1.

Rev. B

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1/09—Revision 0: Initial Version

SPECIFICATIONS

T_A = 25°C, V_S = 3 V, C_X = C_Y = C_Z = 0.1 µF, acceleration = 0 *g*, unless otherwise noted. All minimum and maximum specifications are guaranteed. Typical specifications are not guaranteed.

Table 1.

Parameter	Conditions	Min	Typ	Max	Unit
SENSOR INPUT	Each axis				
Measurement Range		±3	±3.6		*g*
Nonlinearity	% of full scale		±0.3		%
Package Alignment Error			±1		Degrees
Interaxis Alignment Error			±0.1		Degrees
Cross-Axis Sensitivity[1]			±1		%
SENSITIVITY (RATIOMETRIC)[2]	Each axis				
Sensitivity at X_{OUT}, Y_{OUT}, Z_{OUT}	V_S = 3 V	270	300	330	mV/*g*
Sensitivity Change Due to Temperature[3]	V_S = 3 V		±0.01		%/°C
ZERO *g* BIAS LEVEL (RATIOMETRIC)					
0 *g* Voltage at X_{OUT}, Y_{OUT}	V_S = 3 V	1.35	1.5	1.65	V
0 *g* Voltage at Z_{OUT}	V_S = 3 V	1.2	1.5	1.8	V
0 *g* Offset vs. Temperature			±1		m*g*/°C
NOISE PERFORMANCE					
Noise Density X_{OUT}, Y_{OUT}			150		µ*g*/√Hz rms
Noise Density Z_{OUT}			300		µ*g*/√Hz rms
FREQUENCY RESPONSE[4]					
Bandwidth X_{OUT}, Y_{OUT}[5]	No external filter		1600		Hz
Bandwidth Z_{OUT}[5]	No external filter		550		Hz
R_{FILT} Tolerance			32 ± 15%		kΩ
Sensor Resonant Frequency			5.5		kHz
SELF-TEST[6]					
Logic Input Low			+0.6		V
Logic Input High			+2.4		V
ST Actuation Current			+60		µA
Output Change at X_{OUT}	Self-Test 0 to Self-Test 1	−150	−325	−600	mV
Output Change at Y_{OUT}	Self-Test 0 to Self-Test 1	+150	+325	+600	mV
Output Change at Z_{OUT}	Self-Test 0 to Self-Test 1	+150	+550	+1000	mV
OUTPUT AMPLIFIER					
Output Swing Low	No load		0.1		V
Output Swing High	No load		2.8		V
POWER SUPPLY					
Operating Voltage Range		1.8		3.6	V
Supply Current	V_S = 3 V		350		µA
Turn-On Time[7]	No external filter		1		ms
TEMPERATURE					
Operating Temperature Range		−40		+85	°C

[1] Defined as coupling between any two axes.
[2] Sensitivity is essentially ratiometric to V_S.
[3] Defined as the output change from ambient-to-maximum temperature or ambient-to-minimum temperature.
[4] Actual frequency response controlled by user-supplied external filter capacitors (C_X, C_Y, C_Z).
[5] Bandwidth with external capacitors = 1/(2 × π × 32 kΩ × C). For C_X, C_Y = 0.003 µF, bandwidth = 1.6 kHz. For C_Z = 0.01 µF, bandwidth = 500 Hz. For C_X, C_Y, C_Z = 10 µF, bandwidth = 0.5 Hz.
[6] Self-test response changes cubically with V_S.
[7] Turn-on time is dependent on C_X, C_Y, C_Z and is approximately 160 × C_X or C_Y or C_Z + 1 ms, where C_X, C_Y, C_Z are in microfarads (µF).

ABSOLUTE MAXIMUM RATINGS

Table 2.

Parameter	Rating
Acceleration (Any Axis, Unpowered)	10,000 *g*
Acceleration (Any Axis, Powered)	10,000 *g*
V_S	−0.3 V to +3.6 V
All Other Pins	(COM − 0.3 V) to (V_S + 0.3 V)
Output Short-Circuit Duration (Any Pin to Common)	Indefinite
Temperature Range (Powered)	−55°C to +125°C
Temperature Range (Storage)	−65°C to +150°C

Stresses above those listed under Absolute Maximum Ratings may cause permanent damage to the device. This is a stress rating only; functional operation of the device at these or any other conditions above those indicated in the operational section of this specification is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

ESD CAUTION

ESD (electrostatic discharge) sensitive device. Charged devices and circuit boards can discharge without detection. Although this product features patented or proprietary protection circuitry, damage may occur on devices subjected to high energy ESD. Therefore, proper ESD precautions should be taken to avoid performance degradation or loss of functionality.

PIN CONFIGURATION AND FUNCTION DESCRIPTIONS

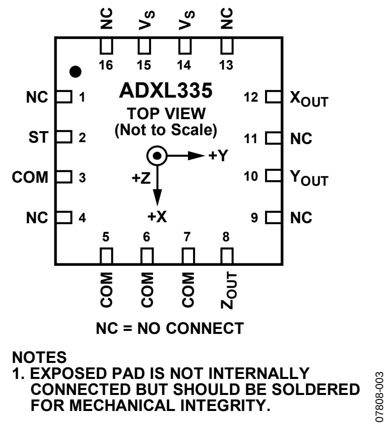

Figure 2. Pin Configuration

Table 3. Pin Function Descriptions

Pin No.	Mnemonic	Description
1	NC	No Connect.[1]
2	ST	Self-Test.
3	COM	Common.
4	NC	No Connect.[1]
5	COM	Common.
6	COM	Common.
7	COM	Common.
8	Z_{OUT}	Z Channel Output.
9	NC	No Connect.[1]
10	Y_{OUT}	Y Channel Output.
11	NC	No Connect. [1]
12	X_{OUT}	X Channel Output.
13	NC	No Connect. [1]
14	V_S	Supply Voltage (1.8 V to 3.6 V).
15	V_S	Supply Voltage (1.8 V to 3.6 V).
16	NC	No Connect. [1]
EP	Exposed Pad	Not internally connected. Solder for mechanical integrity.

[1] NC pins are not internally connected and can be tied to COM pins, unless otherwise noted.

TYPICAL PERFORMANCE CHARACTERISTICS

N > 1000 for all typical performance plots, unless otherwise noted.

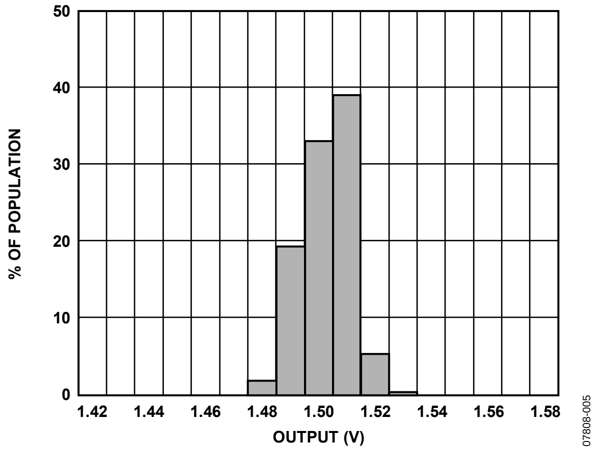

Figure 3. X-Axis Zero g Bias at 25°C, V_S = 3 V

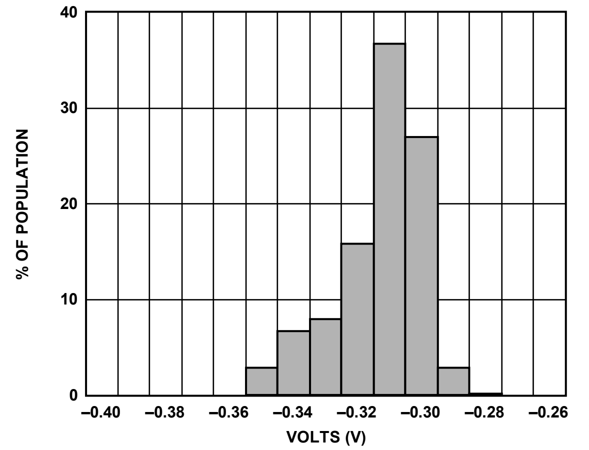

Figure 6. X-Axis Self-Test Response at 25°C, V_S = 3 V

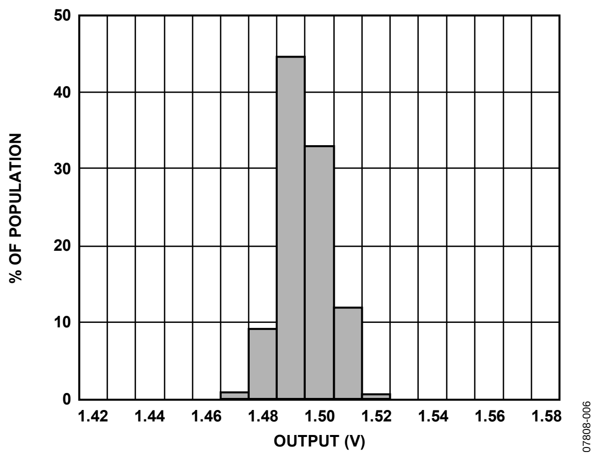

Figure 4. Y-Axis Zero g Bias at 25°C, V_S = 3 V

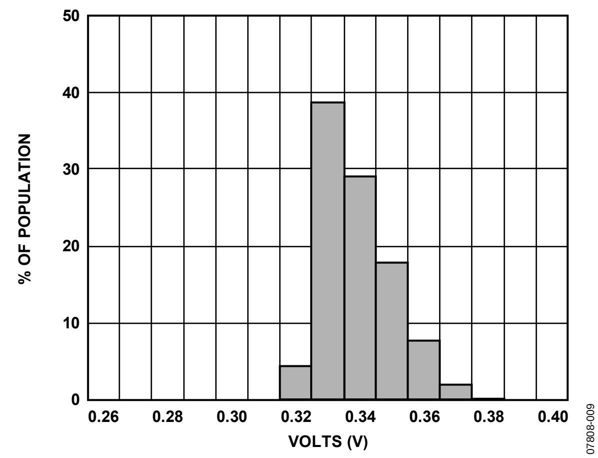

Figure 7. Y-Axis Self-Test Response at 25°C, V_S = 3 V

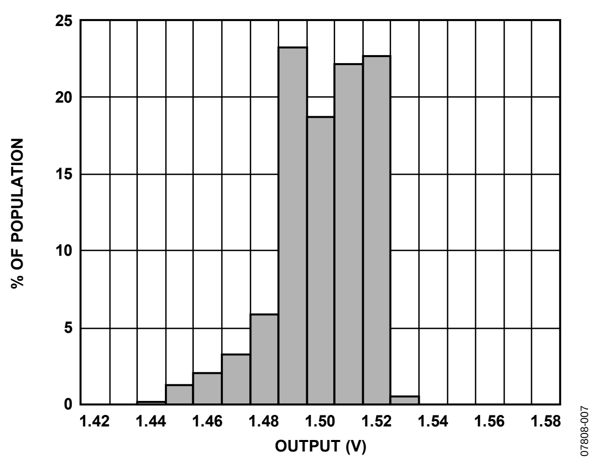

Figure 5. Z-Axis Zero g Bias at 25°C, V_S = 3 V

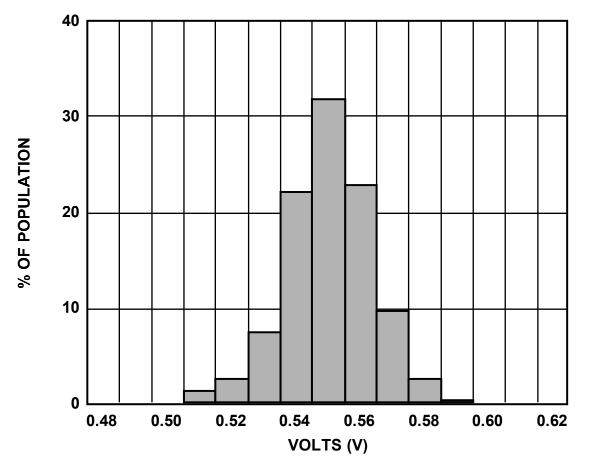

Figure 8. Z-Axis Self-Test Response at 25°C, V_S = 3 V

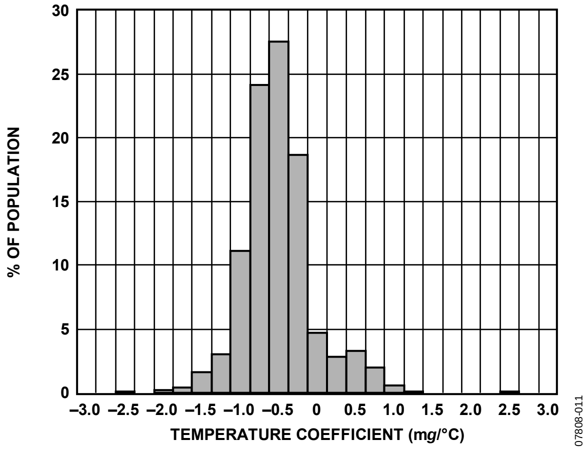

Figure 9. X-Axis Zero g *Bias Temperature Coefficient,* $V_S = 3$ *V*

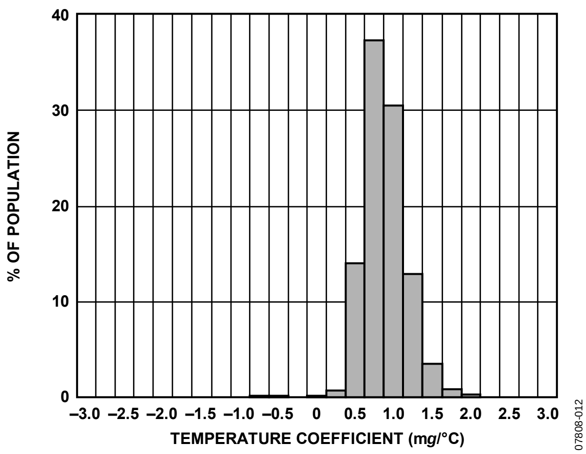

Figure 10. Y-Axis Zero g *Bias Temperature Coefficient,* $V_S = 3$ *V*

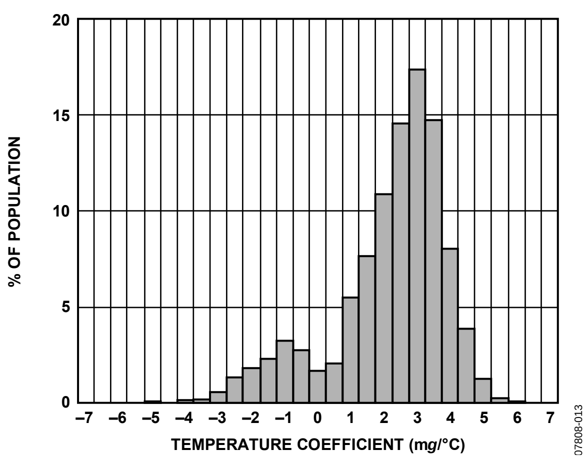

Figure 11. Z-Axis Zero g *Bias Temperature Coefficient,* $V_S = 3$ *V*

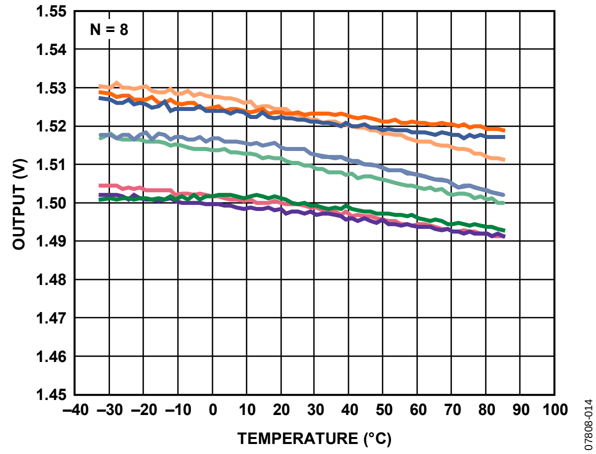

Figure 12. X-Axis Zero g *Bias vs. Temperature—Eight Parts Soldered to PCB*

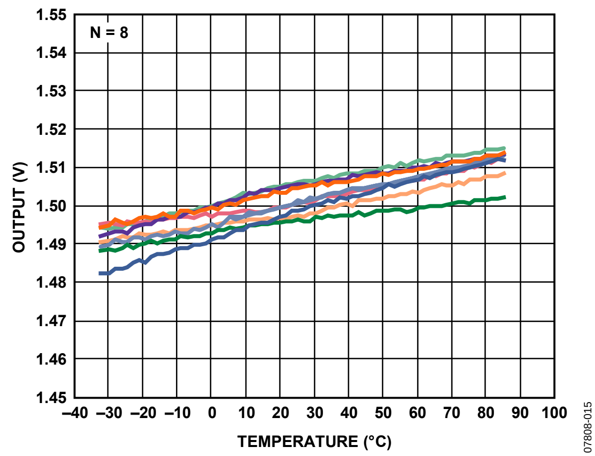

Figure 13. Y-Axis Zero g *Bias vs. Temperature—Eight Parts Soldered to PCB*

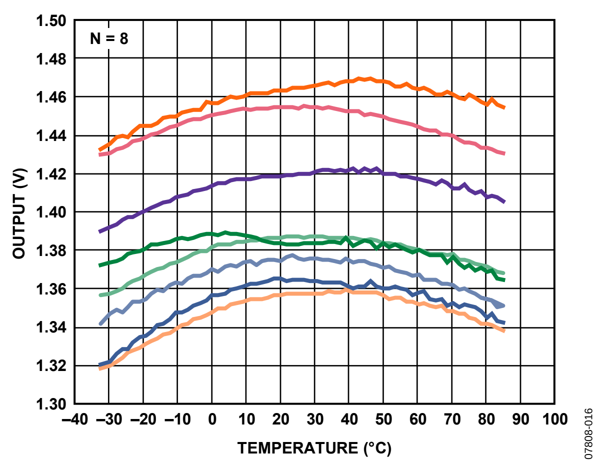

Figure 14. Z-Axis Zero g *Bias vs. Temperature—Eight Parts Soldered to PCB*

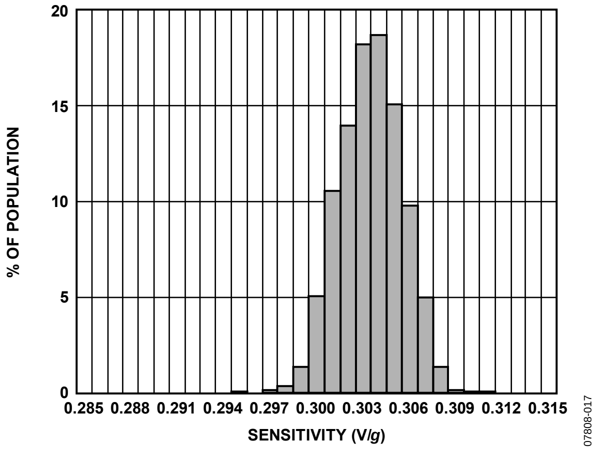

Figure 15. X-Axis Sensitivity at 25°C, V_S = 3 V

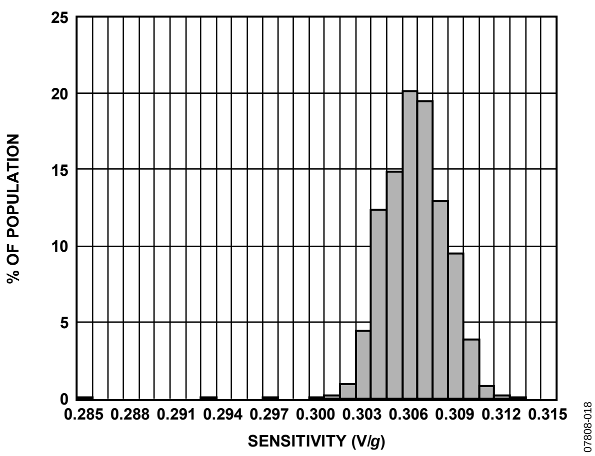

Figure 16. Y-Axis Sensitivity at 25°C, V_S = 3 V

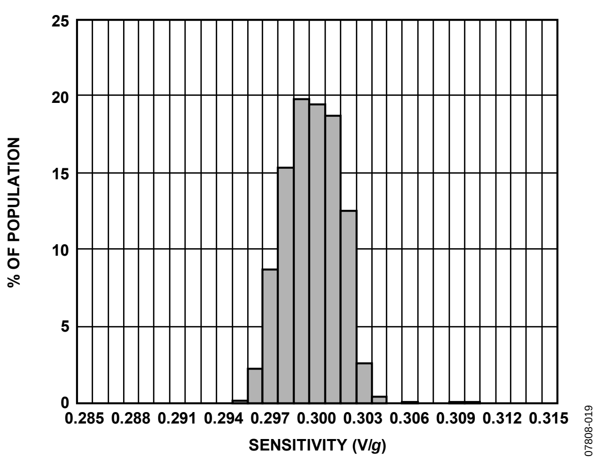

Figure 17. Z-Axis Sensitivity at 25°C, V_S = 3 V

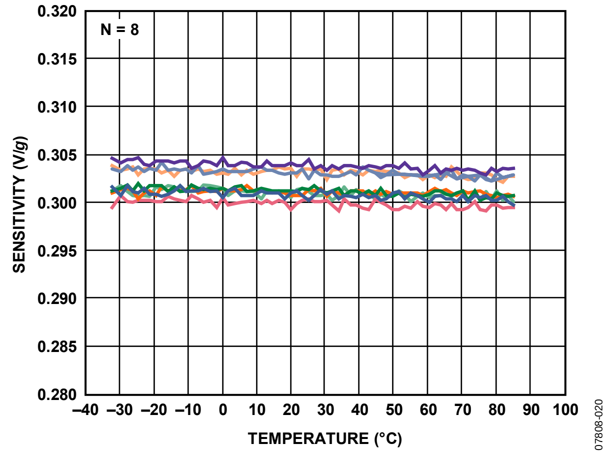

Figure 18. X-Axis Sensitivity vs. Temperature—
Eight Parts Soldered to PCB, V_S = 3 V

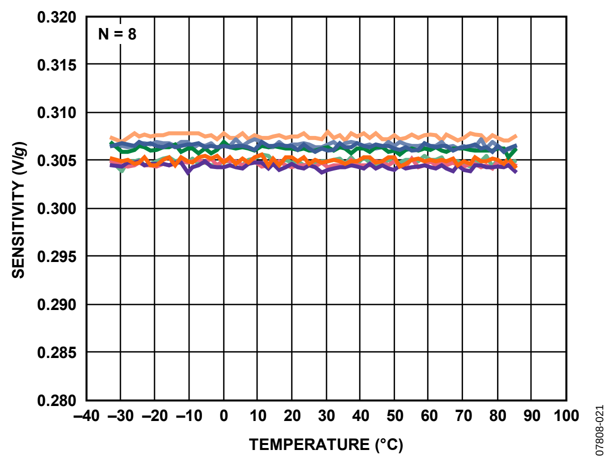

Figure 19. Y-Axis Sensitivity vs. Temperature—
Eight Parts Soldered to PCB, V_S = 3 V

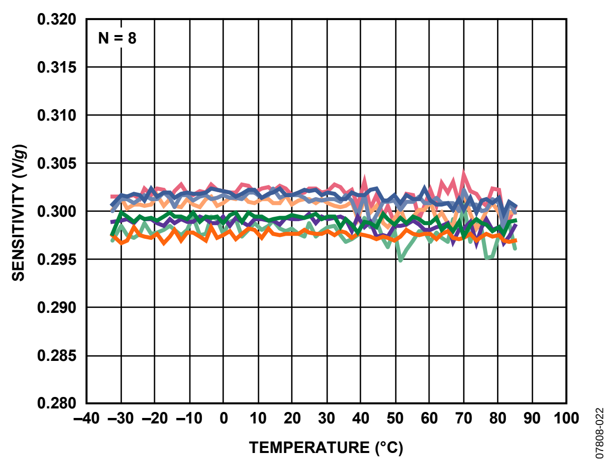

Figure 20. Z-Axis Sensitivity vs. Temperature—
Eight Parts Soldered to PCB, V_S = 3 V

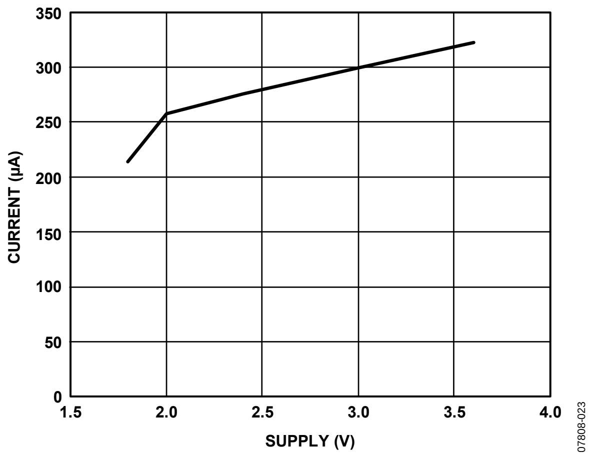

Figure 21. Typical Current Consumption vs. Supply Voltage

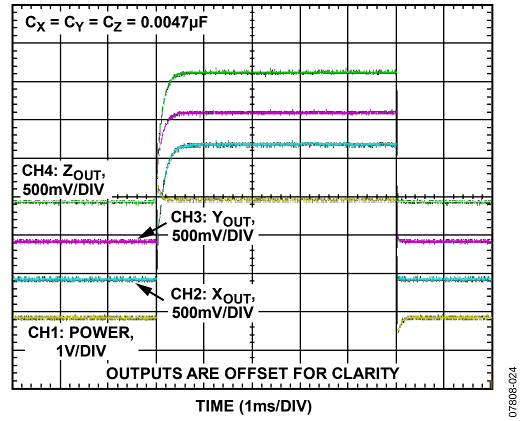

Figure 22. Typical Turn-On Time, V_S = 3 V

THEORY OF OPERATION

The ADXL335 is a complete 3-axis acceleration measurement system. The ADXL335 has a measurement range of ±3 *g* minimum. It contains a polysilicon surface-micromachined sensor and signal conditioning circuitry to implement an open-loop acceleration measurement architecture. The output signals are analog voltages that are proportional to acceleration. The accelerometer can measure the static acceleration of gravity in tilt-sensing applications as well as dynamic acceleration resulting from motion, shock, or vibration.

The sensor is a polysilicon surface-micromachined structure built on top of a silicon wafer. Polysilicon springs suspend the structure over the surface of the wafer and provide a resistance against acceleration forces. Deflection of the structure is measured using a differential capacitor that consists of independent fixed plates and plates attached to the moving mass. The fixed plates are driven by 180° out-of-phase square waves. Acceleration deflects the moving mass and unbalances the differential capacitor resulting in a sensor output whose amplitude is proportional to acceleration. Phase-sensitive demodulation techniques are then used to determine the magnitude and direction of the acceleration.

The demodulator output is amplified and brought off-chip through a 32 kΩ resistor. The user then sets the signal bandwidth of the device by adding a capacitor. This filtering improves measurement resolution and helps prevent aliasing.

MECHANICAL SENSOR

The ADXL335 uses a single structure for sensing the X, Y, and Z axes. As a result, the three axes' sense directions are highly orthogonal and have little cross-axis sensitivity. Mechanical misalignment of the sensor die to the package is the chief source of cross-axis sensitivity. Mechanical misalignment can, of course, be calibrated out at the system level.

PERFORMANCE

Rather than using additional temperature compensation circuitry, innovative design techniques ensure that high performance is built in to the ADXL335. As a result, there is no quantization error or nonmonotonic behavior, and temperature hysteresis is very low (typically less than 3 m*g* over the −25°C to +70°C temperature range).

APPLICATIONS INFORMATION

POWER SUPPLY DECOUPLING

For most applications, a single 0.1 μF capacitor, C_{DC}, placed close to the ADXL335 supply pins adequately decouples the accelerometer from noise on the power supply. However, in applications where noise is present at the 50 kHz internal clock frequency (or any harmonic thereof), additional care in power supply bypassing is required because this noise can cause errors in acceleration measurement.

If additional decoupling is needed, a 100 Ω (or smaller) resistor or ferrite bead can be inserted in the supply line. Additionally, a larger bulk bypass capacitor (1 μF or greater) can be added in parallel to C_{DC}. Ensure that the connection from the ADXL335 ground to the power supply ground is low impedance because noise transmitted through ground has a similar effect to noise transmitted through V_S.

SETTING THE BANDWIDTH USING C_X, C_Y, AND C_Z

The ADXL335 has provisions for band limiting the X_{OUT}, Y_{OUT}, and Z_{OUT} pins. Capacitors must be added at these pins to implement low-pass filtering for antialiasing and noise reduction. The equation for the 3 dB bandwidth is

$$F_{-3\text{ dB}} = 1/(2\pi(32\text{ k}\Omega) \times C_{(X, Y, Z)})$$

or more simply

$$F_{-3\text{ dB}} = 5\ \mu\text{F}/C_{(X, Y, Z)}$$

The tolerance of the internal resistor (R_{FILT}) typically varies as much as ±15% of its nominal value (32 kΩ), and the bandwidth varies accordingly. A minimum capacitance of 0.0047 μF for C_X, C_Y, and C_Z is recommended in all cases.

Table 4. Filter Capacitor Selection, C_X, C_Y, and C_Z

Bandwidth (Hz)	Capacitor (μF)
1	4.7
10	0.47
50	0.10
100	0.05
200	0.027
500	0.01

SELF-TEST

The ST pin controls the self-test feature. When this pin is set to V_S, an electrostatic force is exerted on the accelerometer beam. The resulting movement of the beam allows the user to test if the accelerometer is functional. The typical change in output is −1.08 *g* (corresponding to −325 mV) in the X-axis, +1.08 *g* (or +325 mV) on the Y-axis, and +1.83 *g* (or +550 mV) on the Z-axis. This ST pin can be left open-circuit or connected to common (COM) in normal use.

Never expose the ST pin to voltages greater than V_S + 0.3 V. If this cannot be guaranteed due to the system design (for instance, if there are multiple supply voltages), then a low V_F clamping diode between ST and V_S is recommended.

DESIGN TRADE-OFFS FOR SELECTING FILTER CHARACTERISTICS: THE NOISE/BW TRADE-OFF

The selected accelerometer bandwidth ultimately determines the measurement resolution (smallest detectable acceleration). Filtering can be used to lower the noise floor to improve the resolution of the accelerometer. Resolution is dependent on the analog filter bandwidth at X_{OUT}, Y_{OUT}, and Z_{OUT}.

The output of the ADXL335 has a typical bandwidth of greater than 500 Hz. The user must filter the signal at this point to limit aliasing errors. The analog bandwidth must be no more than half the analog-to-digital sampling frequency to minimize aliasing. The analog bandwidth can be further decreased to reduce noise and improve resolution.

The ADXL335 noise has the characteristics of white Gaussian noise, which contributes equally at all frequencies and is described in terms of μ*g*/√Hz (the noise is proportional to the square root of the accelerometer bandwidth). The user should limit bandwidth to the lowest frequency needed by the application to maximize the resolution and dynamic range of the accelerometer.

With the single-pole, roll-off characteristic, the typical noise of the ADXL335 is determined by

$$rms\ Noise = Noise\ Density \times (\sqrt{BW \times 1.6})$$

It is often useful to know the peak value of the noise. Peak-to-peak noise can only be estimated by statistical methods. Table 5 is useful for estimating the probabilities of exceeding various peak values, given the rms value.

Table 5. Estimation of Peak-to-Peak Noise

Peak-to-Peak Value	% of Time That Noise Exceeds Nominal Peak-to-Peak Value
2 × rms	32
4 × rms	4.6
6 × rms	0.27
8 × rms	0.006

USE WITH OPERATING VOLTAGES OTHER THAN 3 V

The ADXL335 is tested and specified at V_S = 3 V; however, it can be powered with V_S as low as 1.8 V or as high as 3.6 V. Note that some performance parameters change as the supply voltage is varied.

The ADXL335 output is ratiometric, therefore, the output sensitivity (or scale factor) varies proportionally to the supply voltage. At V_S = 3.6 V, the output sensitivity is typically 360 mV/*g*. At V_S = 2 V, the output sensitivity is typically 195 mV/*g*.

The zero *g* bias output is also ratiometric, thus the zero *g* output is nominally equal to $V_S/2$ at all supply voltages.

The output noise is not ratiometric but is absolute in volts; therefore, the noise density decreases as the supply voltage increases. This is because the scale factor (mV/*g*) increases while the noise voltage remains constant. At V_S = 3.6 V, the X-axis and Y-axis noise density is typically 120 μ*g*/√Hz, whereas at V_S = 2 V, the X-axis and Y-axis noise density is typically 270 μ*g*/√Hz.

Self-test response in *g* is roughly proportional to the square of the supply voltage. However, when ratiometricity of sensitivity is factored in with supply voltage, the self-test response in volts is roughly proportional to the cube of the supply voltage. For example, at V_S = 3.6 V, the self-test response for the ADXL335 is approximately −560 mV for the X-axis, +560 mV for the Y-axis, and +950 mV for the Z-axis.

At V_S = 2 V, the self-test response is approximately −96 mV for the X-axis, +96 mV for the Y-axis, and −163 mV for the Z-axis.

The supply current decreases as the supply voltage decreases. Typical current consumption at V_S = 3.6 V is 375 μA, and typical current consumption at V_S = 2 V is 200 μA.

AXES OF ACCELERATION SENSITIVITY

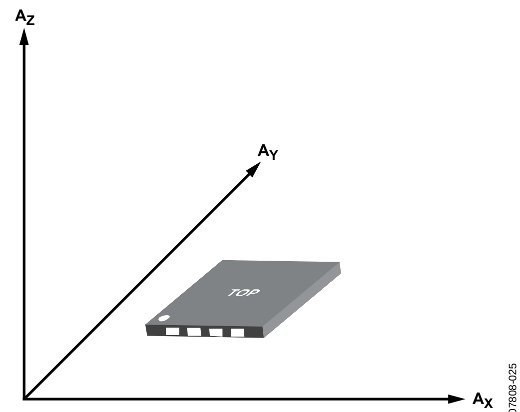

Figure 23. Axes of Acceleration Sensitivity; Corresponding Output Voltage Increases When Accelerated Along the Sensitive Axis.

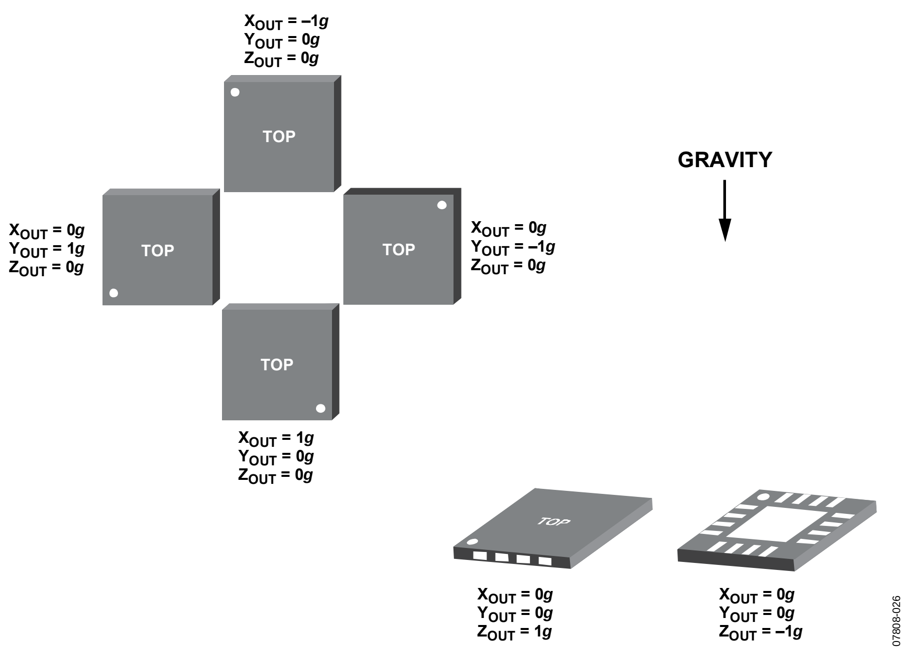

Figure 24. Output Response vs. Orientation to Gravity

LAYOUT AND DESIGN RECOMMENDATIONS

The recommended soldering profile is shown in Figure 25 followed by a description of the profile features in Table 6. The recommended PCB layout or solder land drawing is shown in Figure 26.

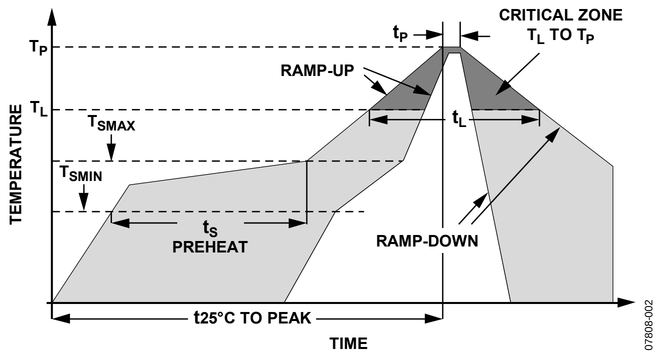

Figure 25. Recommended Soldering Profile

Table 6. Recommended Soldering Profile

Profile Feature	Sn63/Pb37	Pb-Free
Average Ramp Rate (T_L to T_P)	3°C/sec max	3°C/sec max
Preheat		
Minimum Temperature (T_{SMIN})	100°C	150°C
Maximum Temperature (T_{SMAX})	150°C	200°C
Time (T_{SMIN} to T_{SMAX})(t_S)	60 sec to 120 sec	60 sec to 180 sec
T_{SMAX} to T_L		
Ramp-Up Rate	3°C/sec max	3°C/sec max
Time Maintained Above Liquidous (T_L)		
Liquidous Temperature (T_L)	183°C	217°C
Time (t_L)	60 sec to 150 sec	60 sec to 150 sec
Peak Temperature (T_P)	240°C + 0°C/−5°C	260°C + 0°C/−5°C
Time Within 5°C of Actual Peak Temperature (t_P)	10 sec to 30 sec	20 sec to 40 sec
Ramp-Down Rate	6°C/sec max	6°C/sec max
Time 25°C to Peak Temperature	6 minutes max	8 minutes max

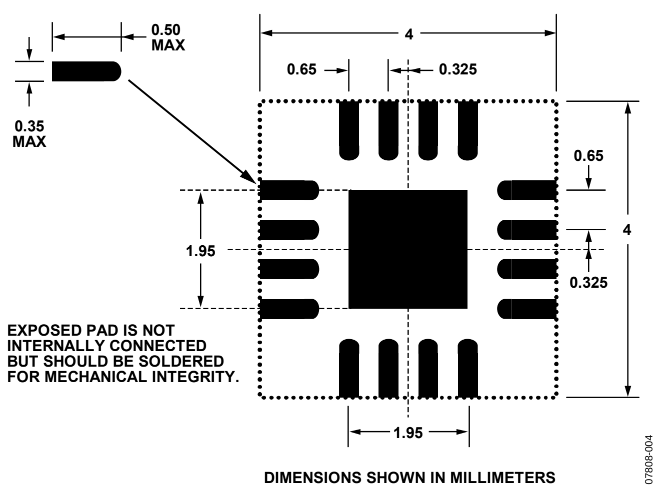

Figure 26. Recommended PCB Layout

OUTLINE DIMENSIONS

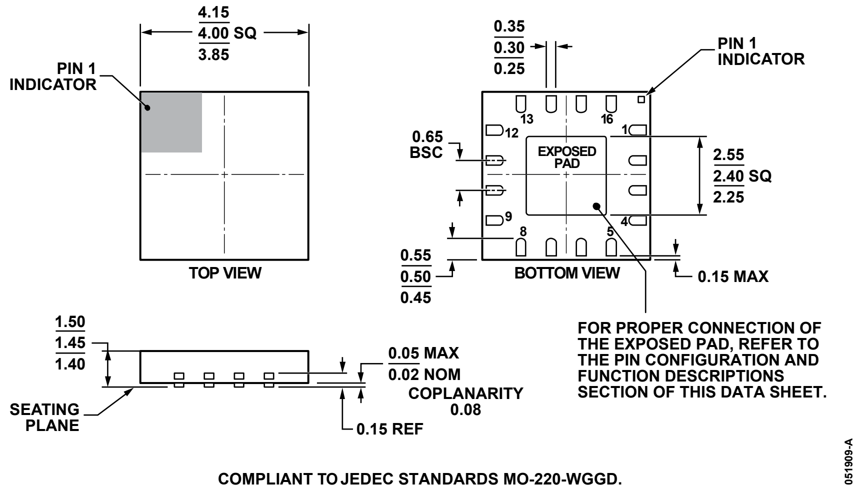

Figure 27. 16-Lead Lead Frame Chip Scale Package [LFCSP_LQ]
4 mm × 4 mm Body, 1.45 mm Thick Quad
(CP-16-14)
Dimensions shown in millimeters

ORDERING GUIDE

Model[1]	Measurement Range	Specified Voltage	Temperature Range	Package Description	Package Option
ADXL335BCPZ	±3 *g*	3 V	−40°C to +85°C	16-Lead LFCSP_LQ	CP-16-14
ADXL335BCPZ–RL	±3 *g*	3 V	−40°C to +85°C	16-Lead LFCSP_LQ	CP-16-14
ADXL335BCPZ–RL7	±3 *g*	3 V	−40°C to +85°C	16-Lead LFCSP_LQ	CP-16-14
EVAL-ADXL335Z				Evaluation Board	

[1] Z = RoHS Compliant Part.

NOTES

NOTES

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Appendix D: Selected Pages from National Instruments USB-6212 Manual

The following pages contain the National Instruments user manual for the USB-6212 data acquisition module used in this project.[66]

DAQ M Series

NI USB-621*x* User Manual

Bus-Powered M Series USB Devices

Français	Deutsch	日本語	한국어	简体中文
		ni.com/manuals		

March 2008
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For further support information, refer to the *Technical Support and Professional Services* appendix. To comment on National Instruments documentation, refer to the National Instruments Web site at `ni.com/info` and enter the info code `feedback`.

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USB-6212/6216 Screw Terminal

USB-6212/6216 Screw Terminal Pinout

Figure A-3 shows the pinout of the USB-6212 Screw Terminal and USB-6216 Screw Terminal.

For a detailed description of each signal, refer to the *I/O Connector Signal Descriptions* section of Chapter 3, *Connector and LED Information*.

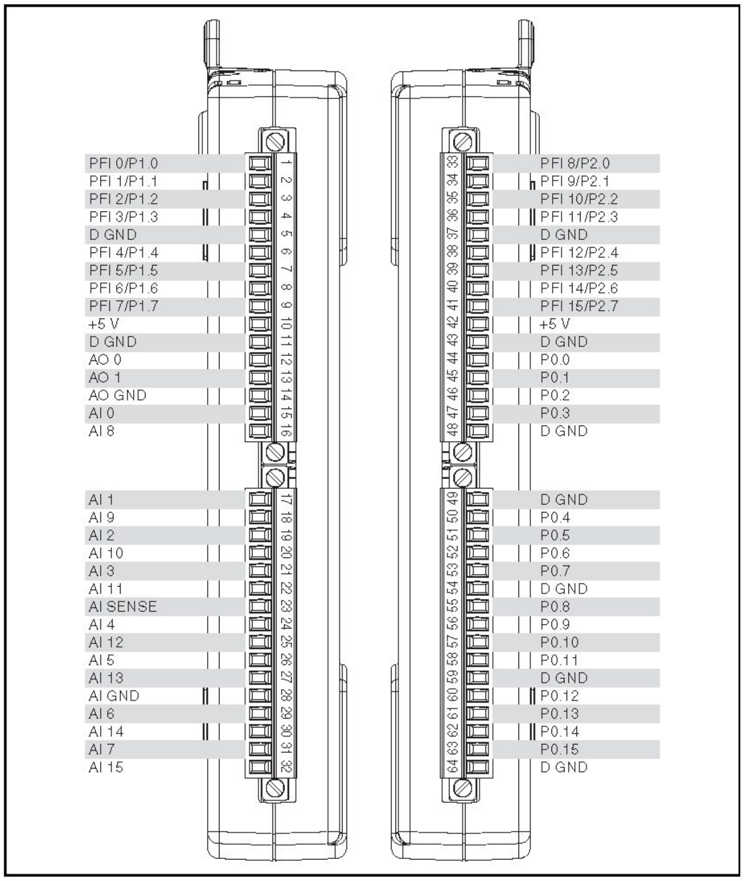

Figure A-3. USB-6212/6216 Screw Terminal Pinout

Appendix E: Pierce Manufacturing Pumpers Brochure

Please refer to the attached data sheet for the Pierce Manufacturing pumpers brochure in PDF format.

Appendix F: Seagrave Fire Apparatus Pumper-Tanker Brochure

Please refer to the attached data sheet for the Seagrave Fire Apparatus pumper-tanker brochure in PDF format.

Appendix G: Seagrave Fire Apparatus Marauder II Brochure

Please refer to the attached data sheet for the Seagrave Fire Apparatus Marauder II brochure in PDF format.

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